The VLA Development Plan

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PREFACE

The Very Large Array has allowed enormous advances in almost all areas of radio astrophysics. Since its dedication almost fifteen years ago, it has been used by more astronomers, and has produced more scientific papers, than any other radio telescope.

Although observing time remains in great demand (the VLA is used by over 600 researchers from over 150 institutions every year) and the VLA's scientific output is still prodigious, key parts of the array still contain the technology of the 1970's. Major improvements in receivers, in the correlator and in broadband signal transmission are needed and are now possible at only moderate cost.

It has been clear for some time that the VLA's impact on astrophysics can be dramatically increased by upgrading or replacing the receivers, data transmission system, and correlator; by improving its frequency coverage; by improving its ability to image large regions of low surface brightness and wide fields of view with a super-compact configuration; and by increasing its angular resolution by adding antennas between the VLA and the VLBA. Some scientific rewards of enhancing the VLA were described to the Bahcall Committee in 1991; their report recommended extending the VLA as a "moderate"-scale new program. More recently, the NRAO has included a comprehensive VLA upgrade in its Long Range Plan for the National Science Foundation.

In January 1995, the NRAO hosted a workshop to discuss the scientific program of an enhanced VLA. This document is based on the discussions of six working groups during and after this meeting, which was attended by about 60 scientists and engineers from the NRAO and VLA user institutes. It illustrates—but likely does not exhaust—the rich astronomical opportunities offered by an enhanced VLA. It outlines capabilities that could transform research in areas ranging from the nearby Solar System to the furthest reaches of the Universe. It also aims to identify technical issues that now need detailed design studies.

We thank all the workshop participants for their input, and especially the chairs of the working groups for their ongoing help with assembling this report.

We ask all potential users of the enhanced array for feedback both on the scientific programs and on the relative priorities of different enhancements described in this VLA Development Plan. Such feedback will be an essential part of making the VLA again a state-of-the-art instrument, with new and more ambitious scientific goals. E-mail on these topics will be welcomed at `newvla@nrao.edu`.

Progress on the VLA Development Plan will be reported in the NRAO Newsletter, in a memo series, and on the World-Wide-Web at `http://www.nrao.edu/vla/upgrade/newvla.html`.

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Chapter 1

OVERVIEW

1.1 INTRODUCTION

The VLA has transformed many areas of radio astronomy with a powerful combination of angular resolution and brightness sensitivity. Even so, fifteen years of research with the VLA have also exposed the many ways in which its limitations direct, or bias, our observations. Depending on the field of study, we may be restricted to objects that are unusually luminous examples of their class, or unusually nearby, or not too extended, or in a particular redshift range, because of limits to the VLA design that were accepted in the 1970's. Many of these limits can be greatly relaxed today. A second transformation of the scientific capabilities of the VLA is possible if it could be returned to the state of the art in sensitivity, frequency coverage, angular and spectral resolution. **An enhanced VLA could be a hundred times faster, several times more frequency-agile, and fifty times better at resolving details, for only a few tens of per cent of the replacement cost of the instrument.**

For example, many observing programs are limited (or prohibited!) by sensitivity. The VLA's intermediate-frequency transmission system was designed with a maximum bandwidth of 100 MHz. This limits the sensitivity, particularly above 2 GHz, where wider bandwidths are permitted by the antennas, the feeds, and the interference conditions. These higher frequencies are very attractive for studies of thermal (stellar and circumstellar) sources in the Milky Way, of young supernovae in other galaxies, of polarimetry of the jets from active galactic nuclei, of the dense magnetized media in gas-rich clusters of galaxies, and for examining radio "quiet" source populations at high redshifts. Fiber optic signal transmission could increase the maximum bandwidth to 2 GHz, enabling a huge leap in the VLA's capability in all such astrophysical arenas.

Similarly, the VLA correlator is based on a custom EGL circuit that was the state of the art in the 1970's. Modern designs allow much greater spectral resolution, larger bandwidths, and increased flexibility. By reaching the state of the correlator art *again* in the 1990's, we could, for example, allow complete surveys of the neutral hydrogen gas in the Universe out to $z \sim 0.1$, avoiding any bias in present surveys of the local structure that are based on cataloging galaxies. We could also use an expanded correlator to exploit the sensitivity of broad-band systems to image wide fields of view in the continuum at lower frequencies, *e.g.*, using bandwidth synthesis to image nearby galaxies and to inventory their stellar and interstellar emissions with less bias toward the brightest or most compact features.

The VLA antennas are useful to $\sim$ 45 GHz, and we now have experience with holography to optimize their performance. This increases interest in outfitting the VLA more completely at frequencies above 20 GHz, where we can explore thermal processes around galactic stars, image the structures of protoplanetary disks, detect young supernovae in nearby galaxies, and study CO in galaxies at high redshifts.

The *u-v* coverage of the VLA was optimized for the astrophysical purposes (and the computing context) of the 1970's. Computing limitations, both in software and in hardware, discouraged imaging and deconvolving large fields of view, especially at high angular resolution. These limitations have been reduced to the point where many wide-field and/or high-resolution experiments could now be supported if the VLA had the requisite inner and outer *u-v* coverage. Whether mosaicing large-scale galactic features or entire external galaxies, or making high-resolution images of the interior structures of star-forming regions, circumstellar winds, young supernovae, or jets from galactic X-ray sources and AGNs, we may now be limited by the available *u-v* coverage, not by our ability to compute the images.

Finally, some VLA subsystems were planned but never built for lack of development (infrastructure) funding. The 2.4 GHz system, which has always been of interest for planetary radar experiments and for Faraday depth studies of galactic and extragalactic sources, is now of increasing interest to all continuum projects as RFI from mobile communications systems proliferates at lower frequencies.

It has therefore been clear for some time that the VLA could be made a much more powerful tool for astrophysics at a moderate cost relative to the original investment (in today's dollars). Ideally, its construction would have been followed by funding a timely inflow of new technology into its infrastructure. This would have allowed for a *steady* expansion of its scientific capabilities. But in fact the operating budget has not kept pace with inflation, so only a few high-priority but *incremental* improvements have been possible, some with non-NSF funds. The imbalance between our technical ability to increase the VLA's scientific productivity and our capacity to fund technical improvements has grown steadily. This imbalance may only worsen in future, absent an explicit proposal to the NSF for a major re-capitalization of the VLA hardware.

This document reviews the technical possibilities for enhancing the VLA, and their scientific potential, as a first step toward such a proposal.

1.2 TECHNICAL OVERVIEW

Earlier informal reviews of the scientific motivations for enhancing the VLA identified needs for *major* gains in four areas:

- **Sensitivity**.
- **Frequency coverage**
- **Spectral line resolution, bandwidth, and flexibility**.
- **Angular resolution**.

The following technical capabilities are therefore key ingredients in a VLA Development Plan:

Phase 1: An Ultra-Sensitive Array

- **New receivers**: lower noise temperatures and much wider bandwidth performance ($\approx$1 GHz in each polarization channel) in existing bands; add 2.4 GHz and 33 GHz bands at the Cassegrain focus; complete the outfitting at the 40-50 GHz band; extend the 1.4 GHz band to lower frequencies.
- A **fiber-optic data transmission system** to transmit the broadband signals and monitor data, replacing the original waveguide.

- A **new correlator**, able to support ≥ 32 antennas, to process both broadband continuum signals and to provide improved resolution and flexibility for spectral line work.
- **New antenna stations** for a "super-compact" E configuration to enable fast mosaicing of large fields.

Phase 2: The VLA Expansion

- **New antennas** to provide now-unavailable baselines between those in the VLA and in the VLBA.
- **Fiber-optic links** between the VLA and the inner VLBA antennas, and between the VLA and the proposed new antennas.

The combination of these enhancements will yield an instrument with many fundamentally new capabilities. The continuum sensitivity will improve by more than an order of magnitude in some bands (Table 1.2). New and powerful spectral line observations will be possible and significantly more frequency choices will be available. The super-compact E configuration will allow fast imaging of large fields and large objects, greatly enhancing the capabilities of surveys. Linkages to the innermost VLBA antennas and the new antennas will increase the maximum angular resolution by a factor of seven. The sensitivity increases will allow the increase in angular resolution to be exploited fully when observing a wide (and in many cases for the first time, representative) variety of thermal and nonthermal objects, both galactic and extragalactic. Each of these project elements is now discussed in more detail.

1.2.1 Antenna and Receiver Improvements

At the antennas, the project involves: i) improving receivers at existing observing bands; ii) adding new observing bands; and, iii) modifying the antenna structure for improved operation.

Improved Low Noise Receivers

The VLA receivers have been upgraded gradually since the early 1980s. Initially, better low-noise amplifiers were used in existing receivers. More recent systems have used the VLBA design, in which the receiver is attached directly to the feed and the polarizer is cooled in the cryogenic dewar. This design reduces the noise contribution from the polarizer and eliminates long, ambient temperature waveguide runs that added to the system temperature.

The "VLBA-style" receivers are now used at 1.4, 8.4, and 40–50 GHz. These receivers will remain with perhaps only minor modification. The greatest improvement in system temperature can be made in the 5, 15, and 22 GHz bands using the VLBA-style receivers and modern HFET amplifiers. Completely new receivers will be built for these bands, and should reduce the system temperatures by up to a factor of 3. The new receivers will also provide $\approx$1 GHz bandwidth per polarization channel (needed for continuum sensitivity) and will tune over a wider frequency range (to include spectral lines, *e.g.*, methanol, whose astrophysical significance was unknown when the VLA was built). Current plans call for bandwidth ratios of order 1.4–1.5:1 in many bands.

At present, only ten VLA antennas are outfitted for 40–50 GHz operation; this band will be made available on all antennas.

New Observing Bands at the Cassegrain Focus

Two new receiver systems will be added at the Cassegrain focus: 2.4 GHz and 33 GHz. A stand-alone 2.4 GHz feed will fit on the feed ring at the Cassegrain focus and will give higher performance

Table 1.1: Proposed VLA Cassegrain Observing Bands

Band	Range (GHz)	Bandwidth (GHz)	BW Ratio	
L	1.20-1.75	0.55	1.46	Upgrade
S	2.13-2.70	0.57	1.27	New
C	4.80-6.70	1.90	1.40	Upgrade
X	8.00-9.10	1.10	1.14	Unchanged
Ku	12.00-18.00	6.00	1.50	Upgrade
K	18.00-26.50	8.50	1.47	Upgrade
Ka	26.50-40.00	13.50	1.51	New
Q	40.00-50.00	10.0	1.25	Complete

than, *e.g.*, an 1.4 GHz/2.4 GHz dual-band feed such as that used on the Australia Telescope. The 2.4 GHz band is potentially the highest sensitivity VLA band. It will also let the VLA participate in bistatic planetary radar observations with Arecibo Observatory. The 33 GHz band can also support bistatic radar experiments with the Goldstone 70 m antenna and would allow imaging of many interesting molecular lines, including red-shifted CO. Table 1.1 summarizes the proposed new and upgraded VLA Cassegrain observing bands.

New Prime Focus Systems

Plans for new prime focus receiver systems are less well defined. A 330 MHz system is currently located at the prime focus, as is a low-performance, dismountable 74 MHz system on 8 antennas. The presence of the 74 MHz dipole feed degrades performance of the 1.4 GHz band by about 10%. Hence, if 74 MHz feeds are deployed on all antennas, it must be possible to dismount them (or otherwise move them from the prime focus position by mechanical means).

Other specific proposals for prime focus systems include:

- A new system covering 580–640 MHz, matching that of the VLBA.
- A broadband UHF ($\lesssim$150–600 MHz) system, including a low-performance system for solar work.
- A sensitive 800–1200 MHz system.

Sensitivity Goals

Table 1.2 compares the continuum sensitivity of the current instrument to that we hope to achieve. We assume a maximum useable bandwidth with RFI excision at the lower frequencies, and add an atmospheric contribution where relevant. The number under ΔS refers to the continuum sensitivity in μJy/beam achieved in 12 hrs integration, summing over two orthogonal polarizations. The total bandwidth assumed for 0.33, 0.60, 1.0, 1.4, and 2.4 GHz is 50, 100, 200, 500, and 1000 MHz, respectively. All other estimates assume 2 GHz net bandwidth.

1.2.2 A New LO/IF Transmission System

To transmit $\sim$2 GHz of bandwidth from each antenna, we will use optical fiber links to all of the VLA stations, to the nearby VLBA antennas and to new antennas between the VLA and present

Table 1.2: VLA Sensitivity

	Enhanced	VLA	Current	VLA
Band (cm)	T_{sys} (K)	ΔS (μJy)	T_{sys} (K)	$\Delta S_{current}$ (μJy)
90	80-135	40-70	150	120
50	45-90	13-25	-	-
30	25-32	5.3	-	-
20	30	2.7	33	6.0
11	31	1.9	-	-
6	29	1.3	45	6.7
3.6	31	1.3	31	4.4
2	37	1.7	110	20
1.3	50-70	2.6	160	37
0.9	38	2.0	-	-
0.7	55	3.5	80	165
0.6	170	15	-	-

VLBA stations (§1.2.5). Separate fibers will carry the LO reference signal and the wide-band IF signal. Between four and six single mode fibers will run to each antenna station. Although low temperature coefficient fiber will be used on runs exposed to ambient temperature, a round trip phase correction system probably will still be needed.

1.2.3 A New Correlator

The specifications for a new correlator are still under discussion (see Chapter 5), as is the architecture best suited to meet them. It is not yet clear whether the more appropriate architecture is a lag correlator, as presently used at the VLA, or an FX correlator, as used by the VLBA. A detailed design study is needed to choose between the two options. Note that the product of the number of antennas, N, and the maximum bandwidth, B, analyzed by the correlator is $N \times B \sim 64$ GHz. This "figure of merit" for the correlator is comparable to that of the Millimeter Array ($N \times B = 80$ GHz); both correlators will be at least an order of magnitude larger than the existing VLA correlator ($N \times B = 5.4$ GHz) or the VLBA correlator ($N \times B = 2.6$ GHz).

The new correlator should be able to process data from at least 32 antennas and have enough delay to accommodate baselines up to 500 km. It could then process some combination of the twenty-seven VLA antennas, two or three of the innermost VLBA antennas (those at Pie Town, Los Alamos, and Fort Davis), and up to four new antennas on baselines between those in the VLA and in the VLBA (§1.2.5).

1.2.4 Improved Surface-Brightness Sensitivity

When the VLA was designed, most astronomers were not overly concerned with good sensitivity to low surface brightness features, with imaging of fields of view wider than its primary beam, or with imaging at angular resolutions below that provided by the D configuration. Mosaicing had not been developed and it was believed that, in any case, such issues were better addressed by large single dish instruments. It is now recognized that compact arrays with total power capabilities fill a gap between the imaging capabilities of conventional interferometer arrays and those of large single dishes. An ultra-compact E configuration with maximum baseline lengths of a few $\times 100$ m would provide this capability.

Given that the Arecibo telescope (for example) samples a similar aperture how, specifically, do the capabilities of an E configuration compare with those of such a large single dish? The single dish has superior point-source sensitivity—the 225-m aperture that is illuminated at Arecibo would be ≈ 3 to 4 times more sensitive than the proposed E configuration. The basic advantage of an ultra-compact array is its *imaging* capability, *e.g.*, the proposed E configuration could be roughly 10 times faster than Arecibo for survey work. Hence, the main rôle of the E configuration is to provide a fast, low-resolution wide-field imaging capability via mosaicing. The VLA also has access to 85% of the sky (unlike Arecibo, from which $\approx 30\%$ of the sky is visible), and will provide frequency coverage up to 50 GHz. As an interferometer, the VLA also has lower systematic errors than a large single dish; it is less susceptible to pointing errors, and ground pickup is uncorrelated between antennas, as is RFI in many cases.

1.2.5 High Angular Resolution—The A+ Configuration

There is a serious gap in *u*-*v* coverage between the 35-km longest baseline of the VLA and the 200-km shortest baseline of the VLBA. We plan to bridge this gap by allowing some VLA, some VLBA and some new antennas to be used interchangeably as members of either array. These will (a) increase the resolution of the VLA at all frequencies and enlarge the *range* of resolutions over which it has "scaled-array capability", (b) improve the dynamic range, field of view and extended-source sensitivity of the VLBA, and (c) provide the VLBA with a "scaled-array" capability similar to the VLA's, which it presently lacks.

New antennas would be built in New Mexico and Arizona to make the density of *u*-*v* coverage in the 40–400 km baseline range the same as that in the VLBA now beyond 400 km. The first step would be to complete the "Pie Town ring" around the VLA by adding antennas near Dusty, NM and Bernardo, NM. (Linking just the Pie Town antenna to the VLA would double the resolution of the A configuration for northern sources only. Linking the Dusty and Bernardo antennas extends this capability to the whole sky.) The second step would be to add further antennas in the "Los Alamos ring": two possible sites are near Holbrook, AZ and Vaughn, NM. The VLA's delay and fringe rotation systems would be expanded to correlate these signals in real time with the present A configuration (processing would be done at the new 32-station VLA correlator).

Figure 1.1 illustrates how the expanded *u*-*v* coverage in the A+ configuration would improve the imaging of a "twin" of the Cas A supernova remnant at the distance of about 1 Mpc, for example in M 31. The angular extent of the remnant would be about $0''75$. Panel (a) shows the image that could be obtained at λ6cm with the present VLA A configuration. Panel (b) shows the dramatic improvement obtainable with the proposed A+ configuration.

Sub-arc-second resolution observations with the present VLA are possible only at the higher frequencies where the brightness sensitivity needed to detect nonthermal phenomena may be inadequate because of the source spectra. These frequencies may also be inappropriate for any projects in which Faraday depth effects, wide-band spectral shapes, or low-frequency spectral lines are needed to probe source physics at these resolutions. There are also many instances (Chapter 3) where studies of normal stellar radio emission will benefit greatly from increasing both the resolution and sensitivity of the VLA together at higher frequencies.

The reconfigurability of the VLA (its capacity for "scaled array" observations with the same angular resolution at several frequencies) has been vital to its astrophysical success. This distinctive capability of the VLA is now present across the *whole* frequency range from 330 MHz to 22 GHz *only* at resolutions near $5''$. No problem that requires higher angular resolution than $5''$ and full frequency coverage can now be tackled in scaled-array mode. This situation changes dramatically if we can add data from longer baselines in the A+ configuration or the VLBA.

Finally, we note that the availability of optical imagery at $0.1''$ resolution from the Hubble Space Telescope is emphasizing the need for better coverage of this resolution regime over a full

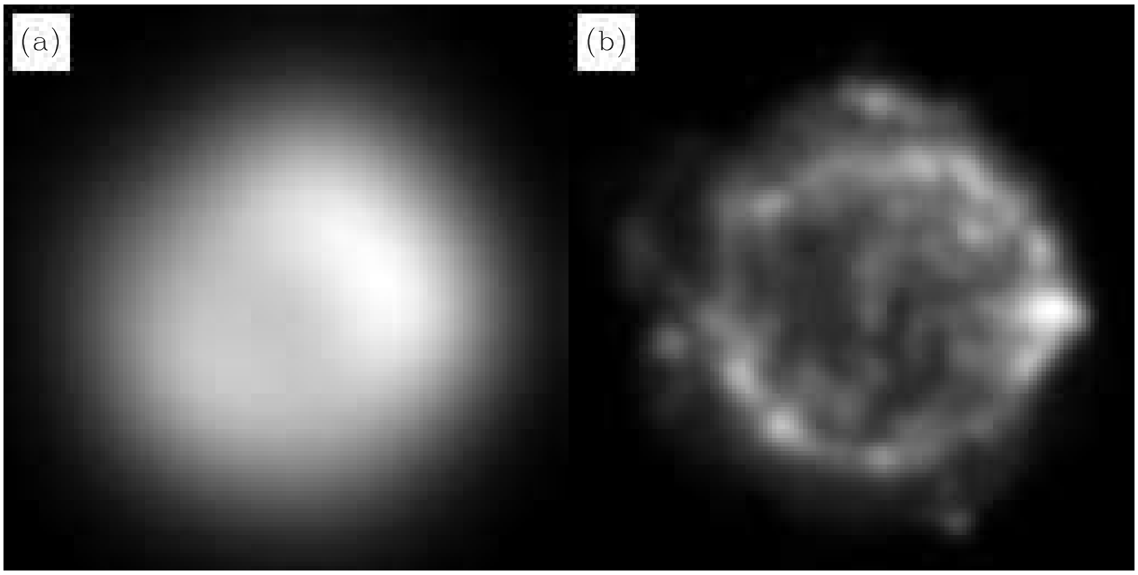


Figure 1.1: (a) An image obtained by using the full u-v coverage of the VLA in the A configuration at λ6cm to sample a model derived from the radio structure of the supernova remnant Cassiopeia A, rescaled to a distance of 1 Mpc. Only a rudimentary indication of shell structure is visible at this resolution (FWHM $\approx 0.3''$). (b) An image obtained by sampling the same model with the full u-v coverage proposed for the A+ configuration. The FWHM of the synthesized beam is about 8 times smaller, revealing many details of the shell and filament structure. Neither simulation is noise-limited.

range of radio frequencies. This resolution falls squarely in the "uncovered gap" between the VLA and VLBA at just the frequencies where imaging would be least corrupted by atmospheric and ionospheric phenomena.

1.2.6 Other Capabilities

Several other instrumental improvements that lead to new scientific capabilities are also being considered. They include: ultra-wide (~35%) bandwidth at the highest frequencies, a robust total power system to support mosaicing, simultaneous multi-band performance (2.4 and 8.4 GHz or 4.9 and 15 GHz), and cross-linking the VLA and VLBA. These are discussed in Chapter 5.

1.3 NEW SCIENCE WITH THE ENHANCED VLA

Chapters 2–4 describe an ambitious scientific program that takes full advantage of the project elements outlined above and imposes demanding performance specifications on the enhanced VLA. In this section, we select a few scientific highlights and mention their impact on the goals of the VLA Development Plan. In making this selection, we emphasize projects for which the VLA Development Plan changes the character of the work that can be done, or introduces entirely new capabilities. Many research programs already active on the VLA will also benefit greatly from the proposed improvements, as also described in Chapters 2–4.

1.3.1 Imaging-Spectroscopy of Solar Radio Bursts

Solar radio bursts have long been observed using dynamic spectra (records of intensity *vs.* time and frequency), only recently that joint spectroscopic and (fixed frequency) imaging experiments have been conducted. An extremely exciting possibility is imaging-spectroscopy of solar radio bursts over an octave of bandwidth, or so, using a broadband UHF system at the prime focus. Using such techniques, it will be possible to constrain the point of origin and the subsequent propagation of both electron beams (type III bursts) and MHD shocks (type II bursts) in the solar corona. As such, it offers a powerful tool for probing coronal dynamics, beam propagation, and shock acceleration.

Unlike other proposals for feeds at the prime focus, the broadband UHF system does not need to be a high performance system. As such, it may require the fewest modifications to the quadrupod and FRM. On the other hand, it imposes demanding specifications on other aspects of the project, requiring:

- A wide-band data transmission system and correlator.
- Dual circular polarization measurements.
- A spectral resolution of ~ 1 MHz and a time resolution as small as 10 ms, which may require the use of a "burst mode".
- Fast, accurate measurements of T_{sys}.

1.3.2 Bistatic Radar Observations of Planets and Minor Bodies

Bistatic radar experiments with the VLA/Goldstone 8.4 GHz system are an unanticipated use of the VLA which have produced a number of exciting results, including: (i) the discovery of ice deposits at the poles of Mercury, (ii) the discovery of the "Stealth" feature on Mars, which produces no detectable echo, and (iii) the discovery that Titan has no deep global ethane/ methane ocean, contrary to expectations.

New 2.4 GHz receivers would enable bistatic radar experiments to be done with both Goldstone and the newly upgraded Arecibo transmitter. JPL is committed to installing a new transmitter on the Goldstone 70 m antenna, operating at ~ 33 GHz, in support of the Cassini mission to Saturn. Hence bistatic radar experiments will be possible in three frequency bands spanning more than a decade in frequency. Furthermore, the VLA will be better able to support future planetary missions if it is equipped for both the 2.4 and 8.4 GHz telemetry bands.

To maximize support of bistatic radar experiments, the VLA Development Plan must include:

- Adding the 2.4 and 33 GHz receivers.
- A correlator with a spectral resolution as high as 5 Hz.
- A correlator which supports simultaneous line and continuum observing as well as simultaneous high- and low-resolution line observing.
- Robust total power measurements.

1.3.3 High-resolution Imaging of Thermal Emission

At present, milli-arcsecond imaging is restricted to objects with high brightness, *i.e.*, nonthermal radio emitters. Large improvements in sensitivity coupled with the A+ configuration would allow imaging of thermal radio sources with milli-arcsecond resolution, opening an entirely new area of astrophysical inquiry. Examples of the kinds of objects which could be imaged out to distances ranging from several hundred pc to several kpc include i) interacting binaries containing giant stars (*e.g.*, symbiotic stars and recurrent novae); ii) stellar winds on giant stars—expansion rates could be measured directly; iii) the early stages of nova outbursts; iv) the photospheres of giant stars, and v) circumstellar disks.

We stress that most elements of the expansion project are required *simultaneously* for these research programs, including:

- A wide-band data transmission system and correlator.
- The A+ configuration.
- Adding the 33 GHz band, completing the outfitting for 40–50 GHz band.
- Correlator flexibility, including support of simultaneous line and continuum observing.

1.3.4 Imaging Proto-planetary Disks

Young stars are expected to be surrounded by proto-planetary disks. To date, they have only been observed in the optical in silhouette against bright nebulae using, *e.g.*, the Hubble Space Telescope. Their inner regions are inaccessible since they are completely opaque to photons at visible wavelengths.

The VLA 40–50 GHz system, when completed on all antennas and supported by a wide-band data transmission system will have three times the angular resolution of the Hubble Space Telescope and 36 times the sensitivity of the present 40–50 GHz system (a factor of 1300 improvement in observing time!). The VLA will be the only instrument able to penetrate the inner regions of proto-planetary disks. The disks are optically thick to shorter wavelengths, and they cannot be resolved at longer wavelengths. Present estimates suggest that roughly 100 proto-planetary disks exist within 200 pc of the Sun with flux densities of 1 mJy/beam ($0.05''$). Such a source could be imaged with a signal-to-noise ratio of 20:1 in 12 hrs.

Technical requirements essentially match those of §1.3.3.

1.3.5 Transient Phenomena

The high sensitivity of the VLA at the high observing frequencies (15 GHz and above) will open a new domain of rapid response to transient phenomena that are initially optically thick at lower frequencies. For example, to observe young extragalactic supernovae in their earliest phases we need to be able to self-calibrate (or phase-reference) sources fainter than 1 mJy in the presence of rapid phase fluctuations in the wider VLA configurations. This is impractical with the current VLA high-frequency systems because of their relatively poor sensitivity and the need for long integration times. The improved high-frequency coverage and wide bandwidths planned for the enhanced VLA will allow good multi-frequency light curves to be obtained for extragalactic supernovae even in their first few days of activity. Rapid response and good data quality for this phase of the outburst are crucial for testing particle acceleration models, and for looking for inhomogeneities and/or instabilities in the emission/absorption region. Similar considerations apply for detection and early imaging of other transient phenomena, such as X-ray transients and flare stars.

Technical requirements include:

- Multiple receivers covering 15–45 GHz.
- Wide-band IF transmission system for maximum sensitivity.

1.3.6 Galactic HI Survey

VLA D-configuration mosaics of relatively small fields of Galactic HI emission reveal complicated filaments and structures on all angular scales. With an ultra-compact antenna configuration it will be possible to survey HI in large parts of the Galactic plane with an angular resolution of $3'$ and a velocity resolution of 0.5 km s^{-1} in a very short time. A survey covering one quadrant and 10 degrees of Galactic latitude would take only 120 hour of observing to complete. A high resolution, fully sampled survey of Galactic HI would provide an important data base for: i) modeling gas dynamics in the Galaxy; ii) comparing HI with molecular gas, allowing detailed modeling of the conversion between atomic and molecular gas in molecular clouds or photodissociation regions; iii) comparison with continuum emission, possibly allowing a distance determination to continuum features if an HI /continuum correlation is found; iv) the study of the interaction between violent events in the disk - SNR, disk blowout events, HII regions – and HI .

Technical requirements include:

- The E configuration.
- Robust total power measurements.
- A wide-band spectral line capability.

1.3.7 Extragalactic HI Surveys

The VLA Development Plan will have a major impact on unbiased surveys in HI . Our view of the large scale structure of the universe, with its large filaments, sheets, walls and voids, is based almost entirely on observations of high-luminosity galaxies, observed at optical wavelengths. Since nearly all investigations of the properties and spatial distribution of galaxies begin with optically (or IRAS) selected galaxy catalogs, any population of gas clouds with very low optical luminosity or surface brightness would largely have escaped detection. Direct searches in the HI line circumvent these optical selection biases. Such searches would make it possible to construct an unbiased HI mass function for the local universe and to probe the evolution of galaxies and the formation of large scale structure in the range $0 < z < 0.8$. Three examples of such surveys are:

- An All Sky HI survey in $0 < z < 0.1$: the good surface brightness sensitivity of the VLA E configuration, combined with the large instantaneous velocity coverage of the new correlator will finally make such a survey feasible.
- The structure of a cluster of galaxies, combined with a pencil beam survey: at higher redshifts an entire cluster can be imaged within one VLA primary beam, *e.g.*, at $z = 0.1$, an Abell diameter is about $20'$. In parallel, a sensitive pencil beam survey can be carried out to sample the entire cone within this primary beam at $0 < z < 0.2$ (RFI permitting).
- The evolution of gas at $0.2 < z < 0.8$: a direct test of how the gas content of galaxies evolves with redshift, using the B configuration to survey a cone to as high a redshift as possible (again, RFI permitting). The large instantaneous velocity coverage of the new correlator will make it possible for a single pointing and LO setting to cover the range $0.2 < z < 0.8$, and to sample a volume of $3.2 \times 10^5 h^{-3}\mathrm{Mpc}^3$. In a 100-hr integration more than thousand galaxies would be detected.

While Arecibo is more sensitive for directed studies, the VLA's large field of view makes it 25 times faster than Arecibo for unbiased HI surveys. At higher redshifts ($z \geq 0.06$) the much higher angular resolution of the VLA is another major advantage.

The technical requirements are as in §1.3.6, with the addition that the 1.4 GHz band should be extended to cover frequencies down to 800 MHz for the high-redshift survey.

1.3.8 Clusters of Galaxies

The nature of the intragalactic medium (IGM) in clusters and groups of galaxies is an important subject for understanding of the large scale properties of the universe. X-ray observations show us this plasma, which exists on a scale of hundreds of kiloparsecs up to at least many Megaparsecs, has hot thermal gas as a major component. However, radio observations show us that in many cases large-scale magnetic fields make up another important component of the medium. The physics of this medium is important in its own right since it represents an extreme environment to investigate complex plasma processes. How ubiquitous and how well organized are the magnetic fields in the IGM? How were they formed ? Are dynamo processes responsible? What rôle do they play in so called "cooling flows"? Is the energy in the magnetic fields, or that imparted to the medium by AGNs, important relative to thermal content of the gas? Are relativistic particles accelerated and/or re-accelerated on large scales? Are they energetically important? What is the range of temperatures in the thermal IGM and how is it regulated? The enhanced VLA will allow significant progress on these issues, primarily through ultra-sensitive observations of i) cluster radio halos; ii) Faraday rotation studies; iii) the Sunyaev-Zeldovich effect; iv) radio galaxies in clusters; and v) gravitational lensing and mass measurements of clusters.

Technical requirements:

- Broad-band data transmission system and correlator,
- Adding 2.4 and 33 GHz receivers,
- The E configuration.

1.3.9 Objects at High Redshift

The VLA Development Plan will open new ways to study the evolution of the radio properties of galaxies with redshift directly. The strong (*i.e.*, AGN) radio source population clearly evolves with cosmological epoch— the apparent density of sources increases rapidly with redshift. This also seems to be true for optically selected, often radio weak or silent, QSOs. Not far below the 3CR flux density limit, most sources are at high redshifts ($z \geq 1$ and many as high as $z = 3$–5). Recently, the IRAS catalog has added a sample in which dust and molecular emission can be detected beyond $z = 2$. Closer by, the Hubble Space Telescope has imaged clusters of galaxies beyond $z = 0.4$, confirming that the Butcher-Oemler effect (the blueing of cluster galaxy populations with redshift) is related to increased star formation in clusters at higher redshifts and that galaxies themselves have different shapes as we look further back. The direct study of the evolution and possibly the formation of galaxies appears to be a real possibility. The enhanced VLA would play a crucial rôle in this arena through detailed exploration of i) the evolution of radio source populations; ii) molecules, dust and free-free emission in distant galaxies; iii) starbursts at high redshifts; and iv) Faraday rotation in magnetized gas-rich environments.

Technical requirements:

- Broad-band data transmission system and correlator,
- Multiple receivers covering 15–50 GHz,
- 2.4 GHz system.

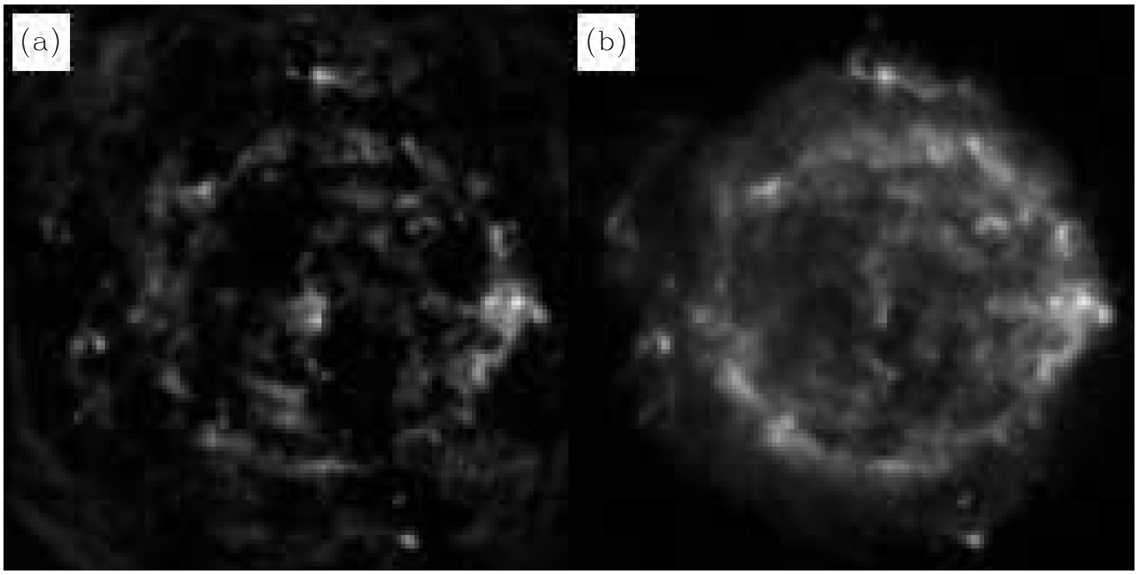


Figure 1.2: (a) An image obtained by using the full u-v coverage of the present VLBA at λ21cm to sample a model derived from the radio structure of the supernova remnant Cassiopeia A, rescaled to a distance of 1 Mpc. Only the most compact emission is represented at this resolution (FWHM $\approx$ 8 milli-arcsec). (b) An image obtained by sampling the same model with the full u-v coverage obtained by adding the Dusty, Bernardo, Holbrook and Vaughn antennas to the VLBA. The FWHM of the synthesized beam increases by only about 4% but the larger-scale structure of the remnant is now correctly represented at this resolution. Neither simulation is noise-limited.

1.4 IMPACT ON SCIENCE WITH THE VLBA

The NRAO now operates 37 "synthesis array elements", broken into a 27-element sub-array (the VLA) and a 10-element sub-array (the VLBA), with only one provision for cross-linking them (using one antenna or the whole VLA in its phased-array mode for VLBI). Much could be gained by allowing individual elements of the VLA and VLBA to join in observations with the other array, especially if we build the new antennas described earlier.

First, the information gathered by an N-element synthesis array varies as the number of baselines, *i.e.*, as N^2 for large N. Linking even four VLA antennas to the VLBA would *double* the information content of VLBA observations by doubling the number of correlations. This doubled information content would translate into improved image quality via (i) a wider field of view, (ii) improved sensitivity to extended structures, and (iii) increased dynamic range (image fidelity) for the VLBA. The more ambitious world-array VLBI experiments have also shown that the apparent simplicity of typical VLBI images reflects a lack of information gathered about the sources more than any intrinsic simplicity of Nature on these scales. We can expect many extragalactic sources to have complex structures on scales from 1 to 100 milli-arcseconds. Physical interpretation of these structures will require images with high dynamic range and wide fields of view over a large range in frequency.

Second, the VLA and VLBA, taken separately, leave the 40–400 km range of baselines relatively unsampled. This "coverage gap" obstructs work on many astrophysical problems. For example, the VLA now images well down to about $0.1''$ FWHM at λ2cm and proportionally lower resolution at longer wavelengths. The VLBA images up to a few milli-arcsec at λ2cm. They fail to meet

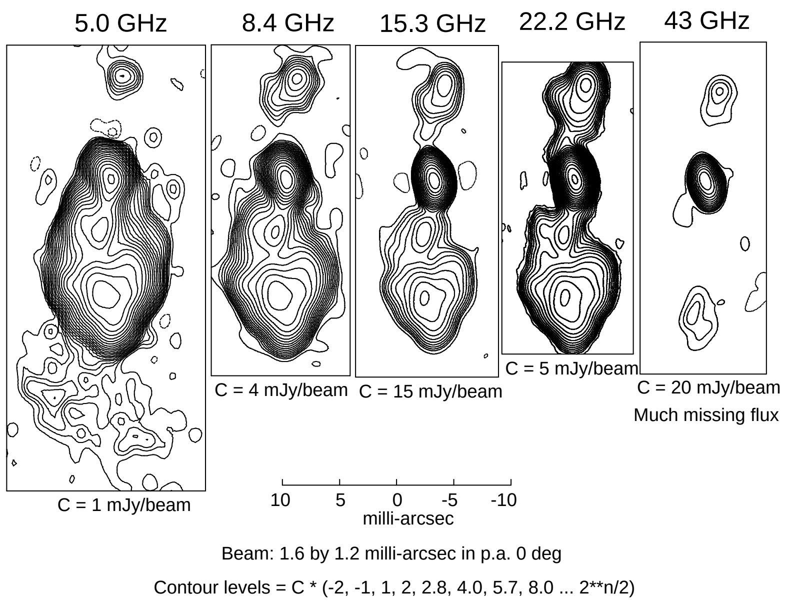


Figure 1.3: Preliminary VLBA images of the nucleus of the active galaxy 3C 84 at five frequencies. Note the differing sensitivities. The extent to which the detailed differences between these images are real frequency-dependent properties of the source (rather than differences in the u-v coverage of the VLBA at these frequencies) would be unclear even with matched sensitivities. The 43-GHz image clearly under-samples the broader (>5 milli-arcsec) structure in the lower-frequency images, however: it accounts for only about 3/4 of the known total flux density. These uncertainties could be eliminated by cross-linking the expanded VLA and the VLBA to provide a scaled-array capability, especially at the highest frequencies.

by about a factor of ten in resolution at any frequency. The missing regime is now of great interest to AGN jet dynamics, observations of galactic X-ray transients, of circumstellar masers, proto-planetary disks, and of supernova remnants in external galaxies.

Figure 1.2 illustrates how the new antennas proposed for the A+ configuration could also improve image quality when used to provide short-baseline u-v coverage in observations with the VLBA. As in Section 1.2.5, we consider observing a "twin" of the Cas A supernova remnant at a distance of about 1 Mpc, so the angular extent of the remnant is about $0.75''$. Panel (a) shows the image that could be obtained at λ21cm with the present VLBA. Panel (b) shows the dramatic improvement obtainable by adding the data from the proposed new antennas.

Third, it is important to realize that the VLBA has very limited "scaled-array" capability because of its small number of antennas (image quality deteriorates rapidly if any antennas are removed at one frequency to "match" the coverage at another), and because it is not reconfigurable. We can have multi-frequency coverage at a fixed angular resolution only by adding data from baselines shorter than 400 km at the higher frequencies (*e.g.*, Figure 1.3). Cross-linking an expanded VLA with the VLBA will extend the scaled-array capability of *both* instruments to cover a huge domain of angular resolution, providing well-filled u-v coverage, scaled with wavelength over a wide frequency range. For example, when studying relativistic jets in AGNs or galactic X-ray transients, we must be able to image total and polarized emissions at the same resolution over a wide range of frequencies to determine spectral energy distributions, Faraday rotations and magnetic field directions, as well as the collimation and proper motion information that are available from single frequencies.

Although a foreign "100-km" array (*e.g.*, MERLIN) can provide some of the "missing coverage" at λ>6cm for northern sources, the high-frequency coverage that is critical to much of the astronomical program, and the N^2 "baseline synergy" with the VLA or VLBA can be obtained *only* with antennas in the Southwestern U.S.

Ultimately, to study how the properties of astronomical sources change with frequency without changing resolution, we should be able to select antenna combinations to create the appropriate set of matched spatial filters for any given multi-frequency experiment. We could do this at high angular resolution if we were able to choose "sub-arrays" that include VLA and VLBA baselines almost interchangeably. The NRAO prepared for this by siting the VLBA antennas around the VLA as their centroid, and by co-locating the main VLA and VLBA operations centers. The VLA Expansion is needed to exploit the unique opportunity that this creates. It gives us a way to transform the scientific capabilities of *two* major instruments significantly at once.

To take full advantage of this, we should also plan to outfit the new antennas and a few existing VLA antennas with VLBA back-ends. The new antennas would be operated as part of the VLBA for much of the time that the VLA is in its more compact configurations and would need VLBA data acquisition systems. It is also desirable to have enough hardware at the VLA site itself to record signals from 4 VLA antennas at once. An upgrade of recording and formatter systems to reach 1 or 2 Gbps in a mode compatible with Mark IV is also desirable. Astrometric VLBI observations would benefit from a 2.4 GHz/8.4 GHz (S/X) dual frequency system.

This Science Workshop was directed only toward examining the astronomical motives for operating the new antennas as the VLA's A+ configuration. A further working group is now being set up to explore the impact of the VLA Extension on science with the VLBA.

1.5 SUMMATION

The VLA Development Plan addresses the demands of a wide variety of scientific programs for greatly increased sensitivity, much broader frequency coverage, enhanced spectral line capabilities, and better angular resolution. It does so largely by returning the VLA to the state-of-the-art in receiver technology, in the transmission and processing of broadband signals, and in correlator design. The scientific requirements also pose new technological challenges. How can optimum performance (polarization and sensitivity) be maintained across the large bandwidths now proposed? Can broadband, high-performance, low-frequency feeds be designed? What is the optimum way to transmit broadband signals from antennas hundreds of kilometers from the VLA for real-time ultra-high-resolution interferometry?

The impact on astrophysics of returning the VLA to the state of the art near the millenium will be profound. Many hard limitations now constraining VLA observations will be removed or greatly relaxed. The continuum sensitivity will increase by ten-fold in several bands. New frequency bands and increased bandwidth ratios will increase frequency coverage almost three-fold. The bandwidth which can be processed by the spectrometer, and its spectral resolution, will simultaneously increase by about 10-fold. The minimum beam area will improve fifty-fold. Finally, the new instrument, when cross-linked with the VLBA, will result in a VLBI instrument with greatly increased dynamic range, field of view and frequency-scalability relative to the present VLBA.

The VLA Development Planthus offers far more than an incremental improvement to existing scientific capabilities, though almost all current areas of research done with the VLA will benefit greatly from it. It provides fundamentally new science in many arenas, much of which depends on the cumulative effect of many improvements in the VLA Development Plan, rather than critically on any one of them. For example, high-resolution imaging of stellar thermal emission requires the sensitivity improvements *and* the A+ configuration; imaging proto-planetary disks requires the 40–50 GHz upgrade *and* enhanced sensitivity; deep H I surveys require extending the 1.4 GHz band to lower frequencies *and* the E configuration.

Chapters 2 to 4 below turn to a detailed description of the scientific program which motivates enhancing the VLA. If past experience is any guide, this initial account of the possible scientific program, while exciting, will prove to be far from complete. Some scientific arenas that will benefit from the enhancement may simply have been overlooked, and innovative uses of the improved instrument will not have been anticipated. Nevertheless, we believe that the science described here clearly demonstrates the need for enhancing the VLA's major capabilities and illustrates how all the key features of the enhancement project will be used in practice.

The science discussions also point to areas where technological challenges exist, and to others where tradeoffs – driven by technological and/or budgetary considerations – are inevitable. These areas are specifically addressed in Chapter 5, which also provides illustrative, but as yet by no means definitive, cost estimates. This Chapter is intended to serve as as background for the detailed studies that will lead to a detailed technical design and better cost estimates.

We strongly urge everyone in the VLA user community to add their thoughts on the astrophysical goals and technical challenges of the enhanced VLA to these discussions. This document is intended to evolve into one that makes the scientific case to the NSF for supporting these enhancements. All comments on it will be welcomed. E-mail comments can be sent to `newvla@nrao.edu`.

Chapter 2

THE SOLAR SYSTEM

Radio observations of the Sun, planets, and minor bodies such as planetary satellites, comets, and asteroids present special problems to synthesis telescopes: all have relatively large apparent motions, many display brightness variations on short timescales due to rotation and/or intrinsic variability, and many possess complex brightness distributions. Yet solar system objects also present special opportunities. The Sun offers an environment where astrophysical phenomena – particle acceleration, MHD shocks, energy transport – can be studied at a level of detail impossible for more distant objects. Similarly, the planets offer a variety of environments where space plasmas, aeronomy, meteorology, and geology can be studied. Furthermore, the interplanetary medium (IPM) is accessible to observation through indirect means which complement *in situ* observations by spacecraft.

Observations of sources in the solar system have led to novel and unanticipated uses of the VLA. The VLA was successfully employed as a downlink for the *Voyager* fly-by of Neptune in the 8.4 GHz band. The addition of the 2.4 GHz band will greatly augment the VLA's ability to offer continued and expanded support in this capacity. As a consequence of the installation of 8.4 GHz receivers in support of the *Voyager* fly-by, bistatic radar experiments with the Goldstone 70 m antenna became possible. Again, the addition of the 2.4 GHz and the 33 GHz bands, will broaden the opportunities for planetary radar experiments.

The special observational opportunities and challenges posed by solar system objects and the IPM set demanding standards for the instrument proposed in the VLA Development Plan. If these standards are met, the VLA will continue to play a major rôle in the exploration of the solar system.

2.1 SOLAR PHYSICS

The Sun is an extremely complex radio source. While there is no shortage of signal – in fact, it must often be attenuated by large factors – its radio emission has structure on angular scales $\lesssim 1''$ (shortward of a few cm) to more than 0.5 deg. Furthermore, the intrinsic brightness distribution varies on timescales ranging from less than one second, to minutes, hours, days, and years. Additional problems are introduced by the Sun's (differential) rotation and apparent motion on the sky.

Aside from being a challenging imaging problem for modern Fourier synthesis telescopes, the Sun presents us with different requirements on the observables. In general, observers of continuum radio emission from cosmic sources are interested in mapping the four Stokes polarization parameters (I, Q, U, and V) with a high degrees of sensitivity, angular resolution, and accuracy at a number of discrete frequencies. Spectral line observers are generally interested in mapping the strength and profile of one or more spectral lines, and the continuum baseline, again with high degrees of sensitivity, angular resolution, and accuracy. In addition, they generally wish to do so with sufficient velocity resolution to resolve the relevant kinematics.

While some solar radio sources are expected to be intrinsically linearly polarized, the linearly polarized component is subsequently washed out by strong differential Faraday rotation as the radiation propagates through the relatively dense, magnetized corona. The observed radiation is unpolarized or circularly polarized, and any information concerning the magnetic field is embodied in the Stokes I and V parameters. Furthermore, spectral lines are absent at wavelengths longer than a few 100 μm – strong collisional and (where relevant) Zeeman broadening make the line profile so broad and shallow that it becomes indistinguishable from the continuum. Hence, high resolution spectral line observations are of limited interest except at meter and decimeter wavelengths (about which, see *Radio Bursts* in 2.1.1). Solar observers gain little by employing state-of-the-art, high sensitivity receivers. The system temperature is overwhelmingly dominated by the source contribution. For example, at λ20cm, the antenna temperature is $T_{\rm ant} \approx 50,000$ K while the receiver temperature is $T_{\rm rx} \approx 35$ K. Finally, solar observations are unlikely to benefit from increasing the angular resolution of the VLA. At wavelengths longward of a few cm, observations are limited in angular resolution by angular broadening on turbulent inhomogeneities in the solar corona to an extent that the Sun is over-resolved by the A and B configurations!

Given the lack of a need for sensitivity, for support of full Stokes polarimetry, for a high resolution spectral line system (at cm wavelengths, at least), or for increased angular resolution, how may the solar physics community benefit from the VLA Development Plan?

2.1.1 The Active Sun

Solar Flares

Solar flares present outstanding theoretical and observational challenges. At issue is by what processes does the Sun first store and then release large quantities of energy? How is the release triggered? How is the free energy subsequently converted into and transported by hot plasma, fast particles, electromagnetic radiation, and mass motions?

X-ray and microwave observations have played key rôles in the study of solar flares because the fast electrons which emit hard X-rays (HXRs) and microwaves carry a significant fraction of the energy liberated during the impulsive phase of a solar flare. HXR emission is produced by thermal bremsstrahlung, as fast electrons are stopped by cool, dense material in the low corona and chromosphere. Microwaves are produced by mildly relativistic electrons gyrating in strong magnetic fields (gyrosynchrotron emission). Both emission mechanisms are well-understood and can be exploited to deduce physical conditions in the source.

HXR spectrometers have been flown on space-based platforms for many years, but HXR imagers are still immature. While ground-based interferometric imaging of flare-associated radio emission has been employed effectively for many years, microwaves remain under-exploited do to a lack of appropriate instruments or instrumental capabilities. In order to fully exploit microwaves as a flare diagnostic the source must be spatially, temporally, and spectrally resolved over a sufficiently large range of frequencies; in addition, the Stokes parameters I and V must be measured since, unlike HXRs, gyrosynchrotron emission depends sensitively on the magnetic field vector. No instrument presently exists which satisfies all of these requirements. While the VLA currently approaches the requirements of high time resolution (it can snapshot image at a rate of 5sec^{-1}) and high spatial resolution, it typically samples only one or two frequencies during the course of a flare. The spectrum of flare-associated microwave emission is therefore only crudely constrained, or is wholly unconstrained. It is therefore extremely important to expand the spectral coverage of the VLA on short timescales.

Spectral coverage at the Cassegrain focus may be acquired in a number of ways:

- A frequency-agile feed could be installed on each antenna. For the purposes of solar observing, it need not be a high-performance system.
- One or more dichroic systems—*e.g.*, a 4.9 GHz/15 GHz system—could be installed on the feed ring
- The existing gaps in frequency coverage could be filled in with new broadband receivers (e.g., the 2.4 and 33 GHz bands).
- In any event, at least two independently tunable IF pairs are desirable. Above all, it must be possible to tune across a given band on short timescales (that is, re-tune and re-establish phase-lock on a timescale $\ll 1$ sec).

The first option is preferred, but may be unworkable if it compromises performance in other bands. Some combination of the remaining possibilities may be feasible.

Another important requirement for observations of highly time variable radio emissions from the Sun is a robust total power system. A fast, linear, high-dynamic-range, and accurate measurement of the system temperature is critical to flare observations since the flare-associated emission often dominates the system temperature and its variation in time.

Radio Bursts

Solar radio bursts at meter and decameter wavelengths were among the first cosmic radio emissions to be studied. Yet many of them defy a detailed explanation. For example, type III bursts are due to mildly relativistic electron beams traversing the solar corona. The beam excites Langmuir waves; the Langmuir waves either scatter or coalesce to produce plasma radiation at the fundamental or harmonic of the electron plasma frequency. Yet the details remain poorly understood. For other burst types (e.g., the millisecond spike bursts) the emission mechanism has not even been unambiguously identified!

With the launch of the Japanese solar-dedicated satellite, *Yohkoh*, the Compton Gamma-Ray Observatory, and the availability of broadband digital radio spectrometers on the ground, there has been a resurgence of interest in solar radio bursts. In particular, joint observations carried out by the VLA and the aforementioned instrumentation has yielded new insights into radio bursts; e.g., the relationship between soft X-ray jets and type III bursts.

The enhanced VLA can have a major impact on our understanding of solar radio bursts. Of key interest is the installation of one or more broadband UHF feeds at the prime focus of each antenna (e.g., 150–300 MHz and/or 300–600 MHz). It will be possible to perform imaging spectroscopy of radio bursts for the first time. Two examples of the importance of such a system must suffice:

- Type II radio bursts are the result of MHD shocks propagating in the corona with speeds ranging from several 100 to >1000 km s^{-1}, and emit at frequencies typically $\lesssim 300$ MHz. It is important to note that essentially all type II radio bursts are associated with coronal mass ejections (CMEs). With the exception of the Culgoora radioheliograph, which mapped type II sources with low resolution at fixed frequencies (80 and 160 MHz) during the 1970's and early 1980's, no instrument has imaged the onset and subsequent propagation of type II sources directly. Since the emission is excited at the fundamental and/or harmonic of the plasma frequency, the frequency of emission depends on the square root of the local electron number density. As the shock propagates outward, the type II drifts to lower frequencies. Imaging spectroscopic techniques offer the means to detect the onset and propagation of

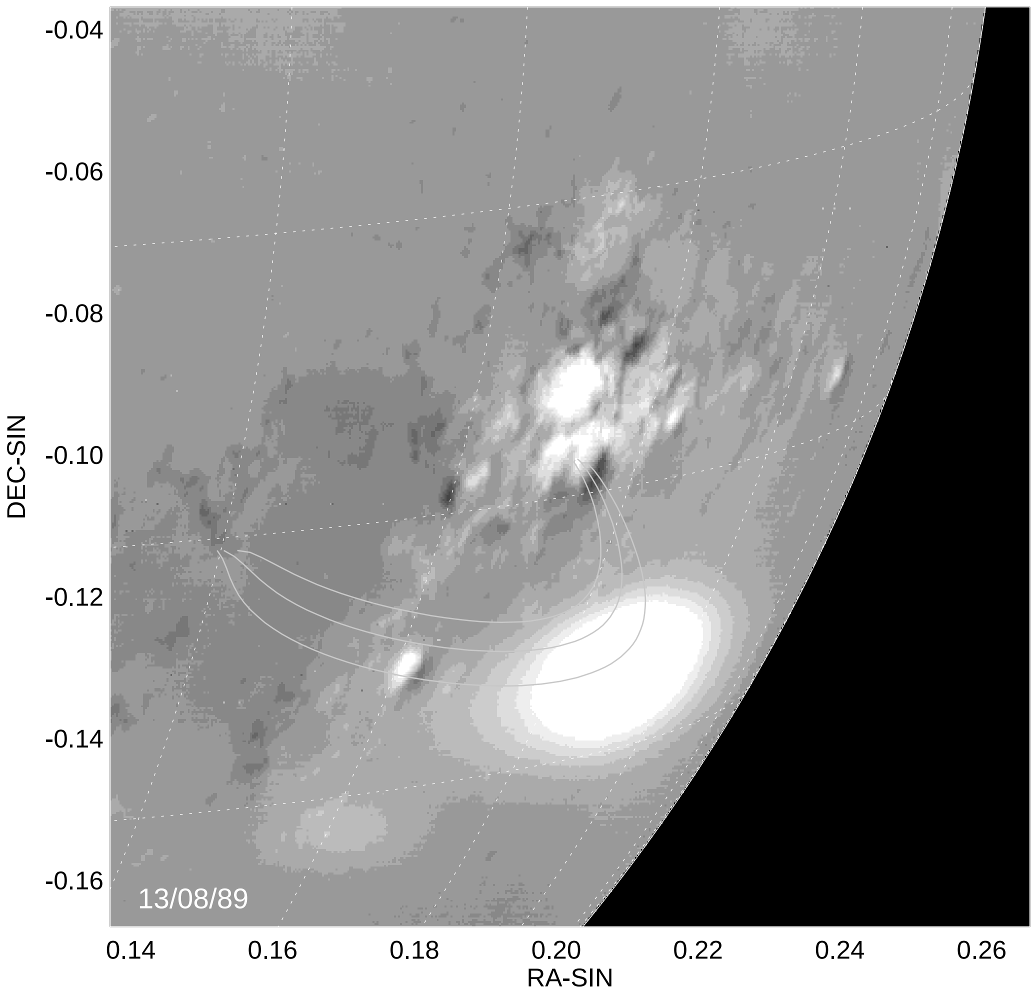


Figure 2.1: Example of type III U-burst. The burst type was identified in a spectrographic record. The longitudinal magnetogram is shown in greyscale. White represents positive magnetic polarity while black represent negative magnetic polarity. Magnetic lines of force resulting from a potential magnetic field extrapolation are shown. The 333 MHz source, imaged by the VLA, is shown in contours.

the shock through the solar corona for the first time. As such, it offers an extraordinary opportunity to study the formation and propagation of MHD shocks, and associated particle acceleration.

- Type III radio bursts are the result of plasma turbulence excited by fast electron beams propagating through the coronal medium. Fig. 2.1 shows an example of a U-burst, a variant of type IIIs wherein the beam is confined to a closed magnetic loop. Like type II bursts, type IIIs emit at the fundamental and/or the harmonic of the plasma frequency, and therefore trace the local electron density. At a single frequency a specific electron density is involved and therefore, a single "height" is visible. If broadband imaging spectroscopy were performed, the trajectory and timing of the electron beam could be determined over a density scale height.

While these two examples are especially vivid, significant insights are sure to come from imaging spectroscopy of the entire "zoo" of radio burst types, including type I bursts, millisecond spike bursts, and a variety of phenomena associated with decimetric emissions (e.g., "patches", quasi-periodic pulsations, "sudden reductions", etc.).

Imaging spectroscopy in the UHF will require the full capabilities of the new correlator and then some. While the requirements on spectral resolution are comparable to those required for applications described elsewhere in this document (~ 512 channels with dual polarization), the need for roughly an octave (or more) of instantaneous bandwidth, and the need to process this bandwidth over very short timescales (~ 10 ms for some experiments), present substantial technical challenges to the project. Given the extremely high data rates involved in the most demanding experiments, it is worth considering a "burst mode", where data are recorded at high rates and later correlated.

Large-scale Transient Phenomena

Coronal Mass Ejections (CMEs) have a major influence on the Earth and the interplanetary medium (IPM), and perhaps play a rôle in the initiation of solar flares. Currently, they are primarily observed by ground- or space-based white–light coronographs, although the SOHO mission will carry a UV coronograph and efforts are underway to design and build ground-based infrared coronographs.

CMEs are often associated with type II radio bursts and imaging spectroscopy of radio bursts is an important goal of solar radiophysics. However, radio bursts involve emission processes which depend on physical parameters in complex and often nonlinear ways. It is therefore also desirable to observe the incoherent (free-free and/or gyrosynchrotron) radio emission associated with CMEs. Because CMEs possess very low surface brightness, a configuration such as the ultra-compact E configuration is needed. Because the Sun itself is a major source of sidelobe confusion, differential techniques may have to be employed (as they are in CME studies at visible wavelengths) to detect incoherent, low-surface-brightness emission from CMEs.

Eruptive prominences are another example of a transient phenomenon, whereby cool prominence material erupts outward from the Sun with speeds up to several 100 km s^{-1}. Eruptive prominences are often accompanied by a CME. Prominence material should be easily detected in microwaves, given sufficient surface brightness sensitivity, because the prominence material is relatively cool and therefore very optically thick to free-free absorption. Because the VLA's field of view decreases with frequency, eruptive prominences will most likely be observed between 3–8 GHz in an ultra-compact array configuration.

Active Regions

Solar active regions are localized areas on the Sun where magnetic flux has erupted through the photosphere into the chromosphere and corona. They are characterized by the presence of sunspots in white light, enhanced line emission (e.g., Hα, CaII), and greatly enhanced soft X-ray (SXR) and radio emission. As their name implies, solar active regions are the sites of solar flares, a variety of radio bursts, enhanced coronal heating, and play a rôle in various mass ejections. A key goal of solar physics is to understand their birth, evolution, and decay, and their production of transient, energetic activity.

Two sources of opacity are relevant in active regions at cm and dm wavelengths. The first is thermal free-free absorption and the second is thermal gyroresonance absorption. Radio waves with frequencies which are low integer multiples of the the electron gyrofrequency ν_B (i.e., $\nu = s\nu_B; s = 1, 2, 3...$) may be resonantly absorbed and emitted by electrons gyrating in the local magnetic field. For example, the electron gyrofrequency in a 580 G magnetic field is $\nu_B = 1.6$ GHz, the third harmonic of which lies in the 4.9 GHz band. Given sufficient spectral and spatial resolution, one can exploit gyroresonance absorption to place unique constraints on the magnetic field at the base of the corona. It works as follows: consider a given frequency ν which is optically thick to gyroresonance absorption in the solar corona at $s = 3$. It therefore yields a brightness temperature which is similar to the effective temperature of the corona ($\mathrm{T_B}(\nu) \approx 3 \times 10^6$ K). Now let ν increase – as ν increases, the resonance condition is matched at higher magnetic field strengths, which occur at lower heights in the corona. At some critical frequency ν_c, the resonance condition is matched at the base of the corona. For $\nu > \nu_c$, $T_B(\nu)$ drops precipitously as the resonance layer traverses the transition region and chromosphere where the effective temperature is much lower. A high resolution map of ν_c may therefore be converted into a map of $|B|$ at the base of the corona. With care, the field vector may also be constrained. Coronal magnetography provides the most direct means available of estimating the magnetic field at these heights. It would provide an invaluable tool for assessing departures of the field from potential configurations in active regions, and for assessing the rôle of electric currents. While the VLA currently provides sufficient angular resolution for this purpose, broadband spectral coverage has been absent. The frequency coverage and the large bandwidth ratios proposed as part of the VLA Development Plan go a long way toward remedying this shortcoming.

A technique somewhat analogous to coronal magnetography can be used at lower frequencies (1–4 GHz) to determine the temperature and mean density of coronal material. At frequencies $\lesssim 4$ GHz the corona above active regions becomes optically thick to free–free absorption. Since the optically–thick layer typically lies above the gyroresonance sources, the character of radio images of active regions changes dramatically between the 1.4 and 4.9 GHz bands (Fig. 2.2). Given sufficient spectral coverage in the range 1.3 - 4 GHz, the same technique of studying radio spectra as a function of position yields the mean temperature (from the optically–thick portion of the spectrum) and the density (from the location of the spectral break where the spectrum changes from the roughly ν^2–shape of an optically thick source to the flat spectrum of an optically–thin source). Again, it is not possible to exploit this technique with the VLA at present due to the gaps in frequency coverage, and the small bandwidth ratios, a shortcoming which is again addressed by the receiver upgrade.

2.1.2 The Quiet Sun

Chromospheric Structure

The solar chromosphere is a highly inhomogeneous layer of the solar atmosphere lying between the relatively cool photosphere and the super-hot corona. Semi-empirical modeling of the chromosphere has largely relied on UV/EUV line measurements, and far-IR and sub-mm continuum brightness

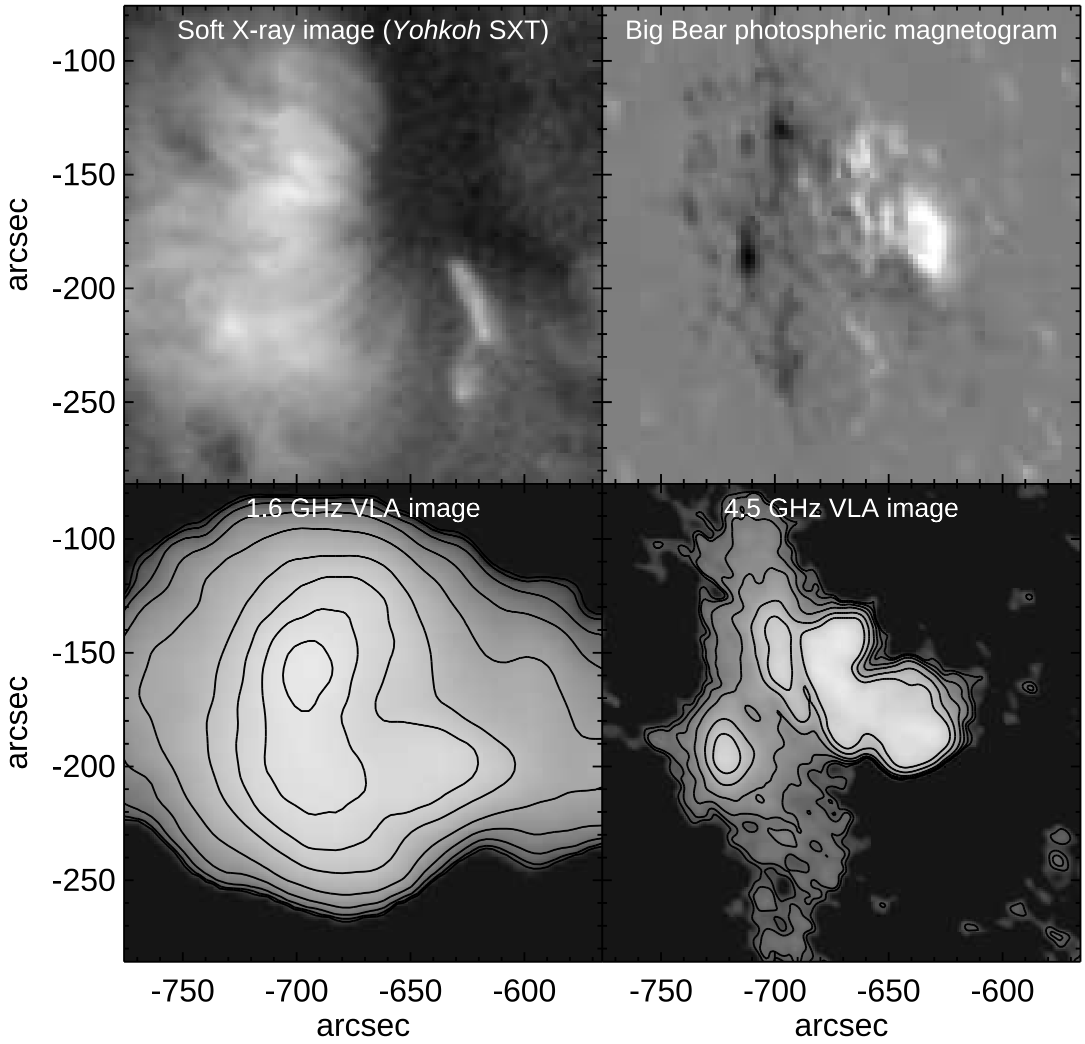


Figure 2.2: Joint radio and SXR images of a solar active region. The upper left frame shows SXR emission from hot (3-5 MK), dense plasma confined by strong magnetic fields. The upper right frame shows the corresponding photospheric magnetogram. The lower left frame shows the 1.6 GHz VLA map while the lower right shows the 4.5 GHz VLA map.

measurements. Interpretation of the UV and EUV lines is complex because most form under conditions of non-local thermodynamic equilibrium (non-LTE) . Radio emission, in contrast, occurs under conditions of LTE and therefore provides observers with a convenient, linear thermometer with which to probe the chromospheric medium.

While there is a general correspondence between the microwave brightness distribution and the supergranular network, point-by-point comparisons between frequencies often reveal striking differences. A general correspondence is also found between the network and decimetric emission, which arises from the transition region and low corona, but decimeter sources are more diffuse and the contrast between the network and cell interiors is significantly reduced in comparison to that found in microwaves. The situation is qualitatively similar to the finding that high-excitation EUV and SXR lines also display less contrast than C IV and other chromospheric lines.

Comparisons of the brightness increment observed between the network and cell interiors are found to be in general agreement with model calculations at centimeter wavelengths. However, the absolute brightness of measurements for wavelengths between roughly 2–20 cm are not in agreement with the semi-empirical models, with the models producing substantially more brightness than is observed.

The problem with VLA observations to date is that they have been conducted at one or two widely separated frequencies. It is difficult to assess and understand the structural differences observed in the brightness distribution. While information is available about the brightness temperature spectrum over the wavelength range relevant to the chromosphere and transition region, it represents a spatial average over complex structure. The proposed receiver upgrades will allow observers to image the chromosphere at many frequencies, sufficient to track the changing brightness with frequency due to the complex changes in opacity with height. In particular, the D configuration, with an accurate total power system, and the expanded 4.9, 8.4, and 15 GHz bands will provide an unprecedented view of the mid-to-upper chromosphere. A super-compact configuration will accomplish the same for the low-to-mid-chromosphere with comparable resolution between 18–50 GHz. Because of the small field of view for frequencies $\gtrsim$12 GHz, a robust total power system in support of mosaicing is especially desirable. And because multi-frequency imaging is critical, it must be possible to tune within a frequency band on a short timescale.

Prominences and Filaments

Prominences and filaments are manifestations of the same phenomenon: the appearance of cool, relatively dense material in the corona along magnetic neutral lines. They tend to be extremely long and filamentary – hence, the name. Filaments are almost always visible in Hα filtergrams of the Sun as features in absorption. They generally reside in chromospheric "filament channels" which appear as regions of somewhat diminished brightness at mm and submm wavelengths. At coronal heights, filaments are embedded in a "filament cavity", a volume of lower coronal density. On the limb, filaments are seen in emission as prominences.

Observations of prominences and filaments in the millimeter and centimeter wavelength bands have most commonly been interpreted in terms of prominence/ corona transition region models wherein the cool, dense prominence is optically thick and is surrounded by a thin sheath through which the temperature increases to coronal values. While these models have been successful in accounting for the radio spectrum of Hα filaments between λ3mm and λ20cm, they have been inconsistent with UV observations to the extent that the models imply far less UV radiation than is observed. In this respect, prominence models suffer from a problem similar to that outlined for the solar chromosphere.

Like the quiet Sun, observations of filaments, prominences, filament channels, and filament cavities would benefit from the increased frequency coverage and the wide bandwidth ratios proposed for the VLA. To date, no high resolution images of filaments and their associated environment have been acquired at more than two widely disparate frequencies.

Coronal Holes

Coronal holes were discovered in the 1970's in SXRs by the ATM on board *Skylab*. They are macroscopic coronal structures whose distinguishing feature is that they are magnetically open. That is, magnetic field rooted in coronal holes does not close back onto the Sun – rather, it opens out into the IPM. The particle number density is 2–10 times lower in coronal holes than in the rest of the corona. Coronal holes therefore appear dark in SXRs. They play a key rôle in modulating the IPM because high–speed solar-wind streams originate in coronal holes. Prominent polar coronal holes appear during the decline to solar minimum, and then wane and disappear as the Sun returns to maximum levels of activity. Hence the structure and evolution of coronal holes, and the rôle they play in modulating the IPM throughout the solar cycle, is of great interest.

Coronal holes are dark at decimetric wavelengths for the same reason that they appear dark in SXRs, the contrast between the quiet Sun and a coronal hole being $\sim 35\%$ at λ20cm. At shorter wavelengths the contrast decreases – near λ1cm, however, contrast reappears in the opposite sense: coronal holes are brighter than the quiet Sun! For wavelengths shortward of a few mm, the contrast again disappears. The reason for the contrast behavior of the chromosphere in coronal holes is presently unknown. With the continuous frequency coverage between 12-50 GHz, the VLA will provide an outstanding opportunity to map the chromospheric structure in coronal holes in detail.

2.2 THE INTERPLANETARY MEDIUM

The interplanetary medium is composed of a tenuous, magnetized plasma which originates with the supersonic solar wind. The IPM is of interest for many reasons. The supersonic outflow interacts with planetary magnetospheres and drives a number of magnetospheric phenomena, including geomagnetic storms on Earth. The IPM modulates the flux of cosmic rays in the inner heliosphere and the details of cosmic ray diffusion and drift through the IPM must be understood in detail in order to infer the spectrum and composition of the cosmic rays incident on the heliosphere. The IPM is itself modulated by solar activity, leading to fast and slow solar wind streams, corotating shocks, and *in situ* particle acceleration. Finally, the details of the structure of the IPM – the rôle of turbulence, waves, and the magnetic field, and their bearing on the spatial spectrum of the IPM – are of great interest for their own sake.

The VLA has played an important rôle in ground-based observations of the solar wind using indirect means. Briefly, interferometers such as those at the VLA are ideally suited for measuring the angular broadening and intensity scintillations of background sources viewed through the solar wind, from which properties of the solar wind turbulence may be deduced: the spectral index, the turbulence level, its degree of anisotropy, and the dissipation scale. In principal, the solar wind velocity can be measured by observing the source diffraction pattern sweeping over the array.

The enhanced VLA will improve studies of this kind in two key respects. Studies of turbulence in the solar wind exploit observations of background cosmic sources which, in the absence of the IPM, would be unresolved by the array. Angular broadening and scintillation are then due solely to the intervening turbulent medium. Such studies therefore rely upon the presence of suitable background sources. The increased continuum sensitivity will enable many more background sources to be exploited as probes of the IPM. Source counts at 5 GHz suggest that there are roughly a factor 15 more sources at 100 mJy than at 1 Jy. To date, the properties of the solar wind turbulence have only been determined for a handful of sources at various elongations and position angles due to the paucity of suitable sources. Access to large numbers of background sources will enable observers to determine the properties of the solar wind turbulence along many lines of sight over the course of a single observing run, thus characterizing the state of turbulence in the outer corona in a more global fashion. Second, since the scattering measure (the line-of-sight integral over the turbulence level) falls of with radius roughly as r^{-4}, the A+ configuration will allow the effects of scattering to be observed on small angular scales. The effects of scattering will therefore be observable over a much larger range of solar elongation, effectively bridging the gap between the VLA A configuration and the VLBA.

2.3 PLANETARY SCIENCE

Perhaps the most far reaching of the advances made in planetary sciences with the VLA were made by the use of bistatic radar. However, this application of the VLA was entirely unanticipated in the original design, and most of the experiments carried out have been severely limited in several ways by instrumental constraints. Although many other VLA studies in planetary sciences have been made successfully, lack of coverage of specific frequencies and lack of sensitivity have proved to be limiting constraints. In addition, the need for better angular resolution than is available with the current VLA (but not as good as the VLBA) is clear. In the following we address specific topics in planetary science which can be uniquely addressed by the enhanced VLA. A final consideration is that future space missions are likely to be smaller and less complex than recent ones. Therefore, it is very important to consider how the VLA can help maximize the return of such missions.

2.3.1 Bistatic Planetary Radar

When an electromagnetic wave is transmitted toward a surface, the amount of energy which is scattered from the surface back to the transmitter is most heavily dependent upon the “roughness” or “texture” of the surface on size scales of the order of the wavelength of the incident electromagnetic wave. Measurement of the reflected power yields information about the radar reflectivity – and therefore the composition – of the surface. Comparison of the scattering seen in the sense of circular polarization opposite to that transmitted (flat-facet reflections from a dielectric) to that seen in the same sense (caused by multiple reflections or by certain types of ices) yields additional information about surface roughness on scales comparable to the wavelength. So, for the 8.4 GHz band, surface structures from slightly sub–cm to some 10’s of cm are most important, and dictate the amount of received flux. Going to longer wavelengths (such as the 2.4 GHz band) provides information on surface roughness at larger scales, approaching 1 m.

Since the early 1960’s, results from planetary radar experiments have been used to help form a more complete understanding of the surfaces of the terrestrial planets. Since the installation of the 8.4 GHz band receivers on the antennas of the VLA in 1988, it has become possible to use it in combination with the Goldstone 70 m antenna to create the most powerful radar instrument in the world. With the Goldstone/VLA instrument, it is possible to image the surfaces of Venus, Mercury and Mars with a spatial resolution as good as 100 km. It is also possible to probe the surfaces of the Galilean satellites and Titan. The results of such experiments are some of the most exciting in recent years in planetary science. Perhaps the most significant – and most unanticipated – of these results was the discovery of ice deposits in the polar regions of Mercury. Other extremely important results came from probing of the ice caps of Mars and finding them mysteriously different from each other, discovery of a huge region near the equator of Mars which reflects no detectable energy (dubbed “Stealth”; Fig. 2.3), and the discovery that Titan has no deep global ethane/methane ocean – contrary to theoretical predictions. The Goldstone/VLA instrument has also been used to image several near–earth asteroids, and an experiment on a comet is planned for the future. While these results are impressive, and similar experiments can and will continue to be performed, the VLA Development Plan will have a major impact on planetary science.

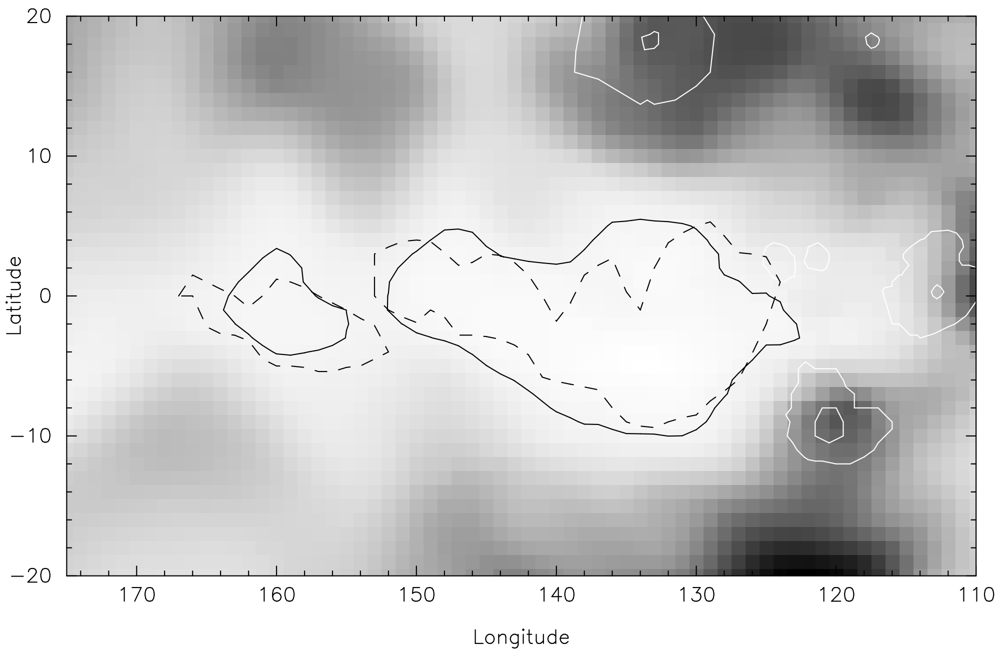


Figure 2.3: This is a simple cylindrical projection of values of the radar cross section of Mars at normal incidence in the same sense polarization. Darker shades represent higher values of cross section. These values are obtained from a fit to the backscatter function of all data points for a particular location on the surface. The region of "Stealth" is shown by the dark outlines. The solid contour encloses locations where the cross section at normal incidence is less than the 1σ noise value. The broken outline is an earlier estimate, from 1988 data only. White outlines denote the approximate geological boundaries of the calderas and shields of the Tharsis volcanoes.

First, the addition of the 2.4 GHz band would be of major interest. Both the Goldstone 70 m, and the Arecibo 305 m antennas, are equipped with powerful 2.4 GHz transmitters, and could be used in combination with the VLA. While the upgraded Arecibo system will have more power ($\sim$1 MW), the Goldstone transmitter ($\sim$420 KW) has full–sky coverage, which is particularly important for radar studies of comets and asteroids. Radar observations at 2.4 GHz, in combination with 8.4 GHz measurements already made, will place constraints on the depth of the very peculiar "Stealth" region of Mars and on the thickness of polar ices on Mars and Mercury could be obtained. While it may seem that Magellan answered all of the questions regarding the surface of Venus, it must be remembered that the radar on Magellan was a single polarization (1 linear), single frequency (2.4 GHz) instrument. A 2.4 GHz system at the VLA would make good polarized measurements of the surface of Venus possible which would greatly enhance the usefulness of the radar data from the Magellan mission. Because of attenuation by the Venusian atmosphere, 8.4 GHz data is severely compromised. The lack of a 2.4 GHz system at the VLA is the one factor preventing very fruitful collaborations with both Arecibo and Goldstone in this area.

Second, in order to support the Cassini mission to Saturn, JPL is committed to installing a Ka-band transmitter. Many technical issues are still not settled, but this may provide another radar frequency at $\sim$30 GHz. The power will be much lower than available 2.4 and 8.4 GHz radar systems ($\approx$20 KW). However, taking into account the theoretical gain of a telescope, the scaling of the return width with frequency and the increased bandwidth of reception, it appears radar between Goldstone and the enhanced VLA in the 33 GHz band would produce a signal to noise ratio of about 1/4 of the current Goldstone/VLA 8.4 GHz system. Therefore, bistatic radar in the 33 GHz band will provide for higher resolution studies of selected objects and extend the frequency coverage available to study surface properties by almost a factor of four.

Third, the new correlator will be of enormous benefit to planetary radar studies in several respects. Because different portions of a rotating planetary surface are approaching the radar line of sight at different velocities, the received radar power is spread in frequency by an amount which depends on the rotational period. For example, in the 8.4 GHz band, the spectral broadening $\delta\nu$ varies from $\approx$27 kHz for Mars to about $\approx$50 Hz for Venus. Typical bandwidths for asteroids are on the order of 100 Hz at 8.4 GHz. The frequency spreads scale linearly with wavelength, so widths in the 2.4 GHz band are about a factor of 4 smaller. With the current system at the VLA, the smallest channel width available is 380 Hz for a single IF. Only the largest of the asteroids are resolved and only if data from one polarization are recorded. For a typical Goldstone/VLA radar experiment, unless one is willing to give up the polarization information, the minimum channel width is 760 Hz. Unfortunately, this is wider than all of the returned signals except for Mars and barely comparable to those from the icy satellites. Because of inadequate resolution, Doppler information is lost and in addition, a penalty is paid in signal to noise ratio, since in those frequencies where there is no radar echo power, there is still noise power. In fact, in order to maximize the signal to noise on a particular surface feature, a channel width equal to the spectral width of that feature is desirable.

The loss of Doppler information limits the experiments in other ways as well. In the case of Titan, such information could be used to calculate the position of the rotational pole, about which almost nothing is known. Determination of the rotational parameters of asteroids could also be done throughout the main belt with the upgraded Arecibo 2.4 GHz transmitter. For these reasons, much higher frequency resolution at the VLA is desired. This is only obtainable with a new correlator with a frequency resolution $\leq$ 5 Hz for all of the bodies except Mars, for which resolution on the order of 100 Hz would be adequate.

In all of these radar experiments, there are two quantities which are currently not measured which would be of much use. The first is the amount of thermal emission contributed to the signal. In some cases this is desired because of the extra information it provides (knowledge of reflectivity and emissivity at the same frequency ties down the surface properties much better), but in others it is essential to interpret the radar data. For objects that contribute significant thermal flux (planets) to the observed signal, some attempt must be made to estimate the thermal emission flux and subtract it out. Currently, that flux is estimated from spectral channels outside of the bandwidth of the received echo flux. However, because work to date has been constrained to be in narrow spectral channels, the total bandwidth of the channels from which thermal emission is estimated is itself very narrow.

The other quantity which is currently not obtainable from VLA/Goldstone radar experiments is the total power (zero–spacing flux), a quantity which is particularly important for planetary observations. These experiments are generally performed in the A configuration to get the highest angular resolution. The price is a serious short spacing problem. This would be alleviated with a total power measurement system. It should be accurate to a few percent, but for our purposes it does not need to be measured often (once every $\sim$15 minutes would be sufficient).

Finally, in order to achieve angular resolution at 2.4 GHz sufficient to permit direct comparisons with 8.4 GHz results, baselines which are about a factor of 4 longer than the longest currently available at the VLA are required. In addition, on these baselines, the polar caps of Mars could also be resolved at 8.4 GHz. The addition of the innermost 4 VLBA antennas (PT, LA, KP, FD) and several new VLA/VLBA antennas would fulfill this need.

2.3.2 The Giant Planets

Observation of the giant planets (Jupiter, Saturn, Uranus, and Neptune) at radio wavelengths have added significantly to our knowledge of their atmospheres. For Jupiter, radio observations have also revealed details of the magnetic field topology and of the distribution of relativistic electrons in the inner magnetosphere. Detailed images of the Jupiter and Saturn have revealed a wealth of phenomena. However, some critical problems can be addressed only with by the enhanced VLA.

Jupiter, Saturn, Uranus and Neptune are gaseous planets primarily composed of molecular hydrogen and helium. The intermediate elements such as C, N, O and S are present in molecular forms in abundances which are crudely solar. Important molecules include NH_3, H_2O, CH_4, CO, and possibly H_2S and NH_4SH. These molecules exist in gaseous forms at large atmospheric pressures and condense out into clouds at points determined by specific thermodynamic conditions along the vertical adiabatic profiles of the various planets. In particular, ammonia becomes saturated and condenses to ice crystals near the 150 K level at about the 1 bar pressure level for all of the giant planets. The water cloud forms near the 270 K levels, which occurs at pressure levels from a few bars on Jupiter but down to 10 to 20 bars on the other planets. The consequence of this is that NH_3 is the major opacity source at centimeter wavelengths on all giant planets and thermally emitted radiation from pressures greater than 1 or 2 bars can only be observed at frequencies significantly less than the broad NH_3 absorption band near 24 GHz. In effect, the major planets have an "ammonia lid" on then which is nearly impenetrable in the wavelength range from about a millimeter to roughly 6 centimeters!

The VLA wavelength gap from 6 to 20 cm greatly limits our ability to map the giant planets in the deep atmospheres, e.g., at the levels of the expected water clouds. A striking example of this limitation is in interpretation of the Comet Shoemaker – Levy 9 impact with Jupiter in July 1994: quantitative analysis of the event depends on the existence or non – existence of the presently unseen water clouds. VLA observation at 20 cm may be sensing emission at the level of the water clouds but the maximum spatial resolution of $\sim 1.2''$ limits the quality of the maps, severely so for Saturn, Uranus and Neptune (which has a maximum diameter of $2.5''$). The water vapor below the putative water clouds is another major opacity source that can't be penetrated at centimeter wavelengths. A VLA capability near λ13cm (2.4 GHz band) would significantly improve our ability to study the deep atmospheres of Saturn and Uranus, in particular. Jupiter is a very important special case since radio maps of that planet at λ20cm and longer are completely dominated by non-thermal emission from the radiation belts. The 2.4 GHz window is ideal for escaping the effects of the ammonia clouds, yet not be completely dominated by the non-thermal emission.

While a 2.4 GHz capability will allow us to significantly improve our understanding of Uranus and Neptune, improvements in spatial resolution are obviously needed. The addition of at least one VLBA antenna into the phase coherent A configuration is vital for real progress and the A+ configuration would be nearly perfect.

2.3.3 The Terrestrial Planets

Mercury

In spite of early space probes, Mercury has retained its distinction as the most difficult to study of the terrestrial planets. Two of the outstanding puzzles can be addressed with the enhanced VLA: the reason for the presence of its magnetic field and its remarkably uniform surface composition.

Mercury's magnetic field apparently requires an active dynamo, which implies the presence of a molten core, yet Mercury is small enough that heat loss should have frozen out the core long ago, as has occurred on the Moon. Various ideas have been offered to resolve this apparent paradox, including (1) an unusually high sulfur content (which lowers the core's freezing temperature), (2) an unusually high abundance of radioactive elements (which adds enough heat to maintain a liquid core), and (3) some means of shutting off volcanic heat piping to the surface (which robs the core of its principal heat-loss mechanism). One of the key (and few) observational constraints on Mercury's internal structure is the net heat flow at the surface, which can in principle be measured with microwave observations of the planet's thermal emission at a wide variety of wavelengths.

A recent attempt to measure this heat flux utilized Mariner 10 IR radiometer measurements of Mercury's night hemisphere and VLA thermal images in the 1.4, 4.9, 8.4, 15, and 22.5 GHz. The microwave spectrum is remarkably flat (Fig. 2.4), which at face value would correspond to a very small heat flux; however, it is quite possible that the 1.4 GHz observations are probing beneath the regolith and into the "megaregolith", a region of highly fragmented rocks and boulders, where the physical parameters (microwave opacity, thermal conductivity, etc.) are very different. Thus, the 1.4 GHz observation may not be useful in constraining the heat flux unless we can understand the nature of the regolith structure at several meters depth.

Measurements at additional frequencies would help considerably. A 2.4 GHz measurement might avoid the megaregolith interface (which seems to be affecting the 1.4 GHz observations), yet provide enough wavelength leverage (between 2.4, 4.9, and 8.4 GHz) to detect the heat flux in a region where the regolith structure is reasonably well understood. Alternatively, measurements at λ30cm, λ50cm, and λ90cm (1000, 600, and 333 MHz, respectively) might help to elucidate the nature of the regolith structure at several meters depth and allow one to utilize the longer wavelengths to constrain the heat flux. Detectability is not a problem at λ30cm and λ50cm with the nominal upgrade sensitivities. Sensitivity starts to become a problem at 90 cm, where only a marginal result could be obtained with the current VLA. However, a 20σ measurement could be obtained in 12 hrs with the upgraded λ90cm sensitivity. The planet can be at least marginally resolved ($\geq 3 \times 3$ pixels) at wavelengths shorter than 30 cm with the A configuration, but becomes a point source at λ90cm.

Several independent lines of evidence (high optical albedo, very low microwave opacity, IR spectroscopy) indicate that Mercury's surface has a very low Fe content. This is very surprising, since conventional models of the planet's evolution incorporate extensive volcanism, which is expected to bring iron-rich, basaltic magma to the surface (as has occurred on the Moon). Yet the entire surface of Mercury appears to be an extreme example of the lunar highlands. Even more surprising is that Mercury's smooth plains are only slightly darker than the Mercurian "highlands", and existing VLA microwave images exhibit no evidence for an enhanced opacity (and hence iron

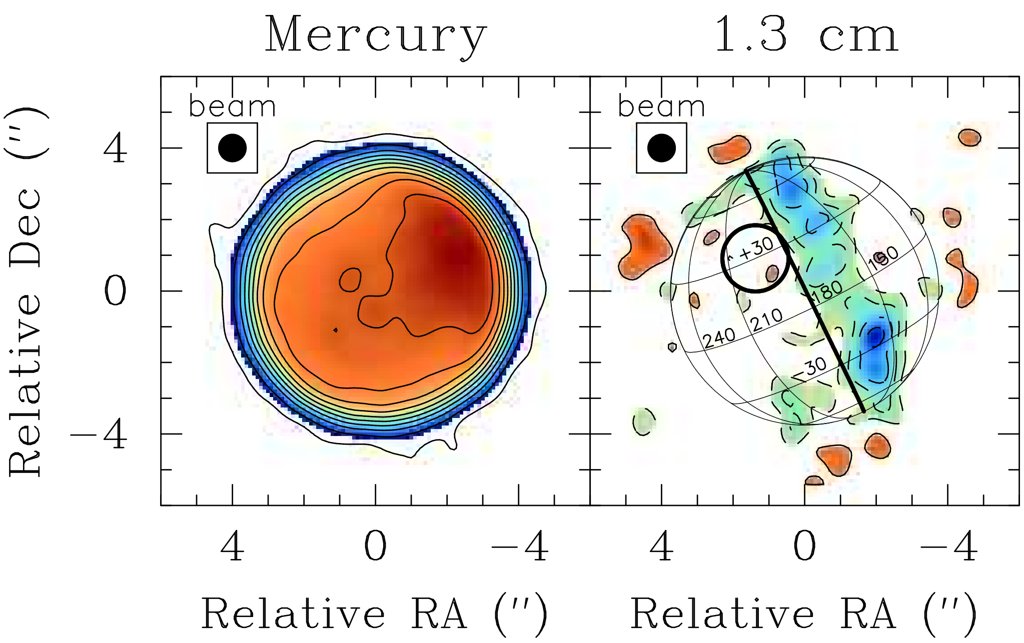


Figure 2.4: A λ1.3cm map of Mercury (left). The contour levels are 10% of the maximum intensity except for the lowest contour, which is 2%. A residual map obtained by subtracting a model map from the observed map is shown on the right. Contour intervals are 5 K. Thermal depressions at both poles and along the sunlit side of the morning terminator are likely due to shadowing by surface topography.

content) within the Caloris basin.

It would be very interesting to actually measure or at least put a much more stringent upper limit to possible microwave opacity variations across Mercury's surface. The only existing image at 22.5 GHz shows no evidence for opacity variations. While it is possible to do a somewhat better job with the existing VLA simply by getting a longer integration in better observing conditions; a much better approach would be to use the 40–50 GHz band, which is much more sensitive to opacity variations because it (1) probes shallower layers where temperature gradients are stronger, (2) provides higher spatial resolution which might reveal opacity variations on smaller spatial scales, and (3) provides three times more SNR than the 22.5 GHz band using nominal parameters of the enhanced VLA. Note that simply using existing millimeter interferometers could not produce images anywhere near as good as the enhanced VLA (27 antennas with 40–50 GHz receivers) – image quality is crucial for such an experiment.

Mars

Because of Mars' rapid rotation, day-night temperature variations penetrate only a shallow $\sim$ 4-cm-deep "diurnal layer", which has an optical depth of $\sim$ 0.3 at K-band, increasing to $\sim$ 0.6 at Q-band. Observations of diurnally modulated temperature variations should provide an excellent probe of the thermal and electrical properties of the Martian surface. Bistatic Goldstone-VLA radar observations at λ3.5cm have identified a "stealth" region with very low reflectivity, which implies a low bulk density and a high microwave emissivity. Thermal measurements at several wavelengths would provide important physical constraints on this region, such as its depth. (Arecibo-VLA radar is another important piece of this investigation – see Section 2.1.) To take full advantage of spatial resolution, one needs the ability to make snapshots of Mars in order to avoid "smearing" caused by the planet's rotation. Sensitivity is not a problem for 1-hour snapshots, but to get high quality images, good UV coverage is very important, which again argues for 27-element capability in the 40–50 GHz band.

Water vapor has been observed in the atmosphere of Mars with the VLA. Because the λ1.35cm H_2O line has a rather small optical depth in the terrestrial atmosphere, it is the most convenient line with which to monitor H_2O in the Martian atmosphere. The amount of water vapor in the Martian atmosphere varies with the Martian seasons. The VLA observations would be improved by improved sensitivity in the 22.5 GHz band.

2.4 MINOR BODIES

The minor bodies (comets, asteroids, and satellites) provide very important information about the formation and evolution of the solar system. Radio astronomical study of these objects is not well developed at present, mainly because of sensitivity problems. The VLA Development Plan will permit a major step forward in these studies.

2.4.1 Asteroids

Thermal emission has been detected from the four largest asteroids: Ceres, Pallas, Vesta, Hygiea, at λ1mm to λ20cm and from a few smaller asteroids at λ2cm. Such measurements place constraints on the thermal and electrical properties of those objects' surface layers. The existing observations indicate that the asteroids studied so far are covered with fine-grained regoliths, which are expected to result from meteoroid bombardment ("sand blasting") of the surfaces over 100's of millions of years. Differences in the microwave spectra of Ceres, Pallas, Vesta, and Hygiea suggest variations in the dielectric properties of those regoliths and/or variations in the regolith thicknesses. However, those few objects represent just a tiny fraction of the thousands of main-belt asteroids, most of which are beyond the detectability of the current VLA. (A 100-km-diameter object at 1 AU distance from the Earth represents a flux of ~ 400 μJy at λ2cm, decreasing to ~ 100 μJy at 8.4 GHz). In addition, there is an important gap in the wavelength coverage from 1 mm to 1 cm. Over this range, the spectra show a distinct drop in brightness temperature. The proposed upgrades in continuum sensitivity and the expansion of wavelength coverage should make a large number of these objects detectable at several wavelengths. Of particular importance is the 40–50 GHz band, which samples the wavelength gap between 1 mm and 1 cm.

2.4.2 The Galilean Satellites and Titan

The Galilean satellites range in maximum angular diameter from $0.9''$ for Europa to $1.48''$ for Ganymede, and Titan's diameter never exceeds $0.9''$. These objects occupy in central position in planetary science, exhibiting a wide range of interesting physical phenomena from hot spots with volcanos on Io to a complex atmosphere more dense than Earth's on Titan. Disk averaged brightness temperatures of these objects have been measured with the VLA and Titan has been extensively studied with the VLA/Goldstone radar configuration, again with essentially full-disk averaging. The enhanced VLA will significantly advance the study of these objects in two important ways. Io and Europa's orbits are very close the surface of Jupiter and confusion from the planet severely affects the measurements of the satellites' disk temperatures as a function of their orbital longitudes. Jupiter's confusing flux density can be minimized by greatly increasing the continuum bandwidth of the VLA. Continuum observations of Io at λ7mm and λ1.3cm should then reveal the variations in mean surface brightness caused by the changes in the viewing geometry as Io orbits Jupiter. The hot spots have been observed only in the IR which is sensitive to the very surface. Measurements at λ7mm and λ1.3cm will probe the hot spots to depths of roughly 10 wavelengths. The subsurface probing is important for all of the satellites. The improvement in sensitivity at λ1.3cm as well as full capability in the 40–50 GHz band are very important for these measurements.

Clearly, the Galilean satellites and Titan are over resolved with the VLBA. However, the A+ configuration is ideally matched to these targets, both for thermal continuum emission at short wavelengths and bistatic radar at 8.4 GHz. If the aperture of that array was weighted to about 100 km, the satellites would be resolved to about 10 beams on a diameter and meaningful maps would be produced. The full A+ configuration could be used with great profit for bistatic radar in the 2.4 GHz band. The radar experiments are necessarily narrow-band and confusion from Jupiter is again a problem for studies of Io.

2.4.3 Comets

While it has long been recognized that the primary outgassing product which drives most of the observable phenomena of comets is H_2O, direct observation of H_2O to date has been possible in only one comet because of interference by terrestrial water vapor. The primary photodisassociation product, OH, can be detected at both UV and radio wavelengths. Only the radio lines can be observed with velocity resolution finer than the outflow velocity. The only cometary images which are resolved both spatially and in velocity have been obtained with the VLA. However, the scale length of OH is fairly large so that in the D configuration typically only 1/2 to 1/3 of the total flux is detected. Because the emission is variable from day to day, the missing spacings must be filled in simultaneously with the VLA observations. The use of the E configuration to increase the surface brightness sensitivity and a total power system to measure the spectra with individual antennas would allow images which contain all of the OH flux. This would unambiguously resolve long-standing uncertainties about the degree of symmetry in outgassing of comets.

So far, only the 1667 MHz transition of OH has been imaged because it is not possible to image multiple transitions with adequate frequency resolution and sensitivity. All four λ18cm OH lines need to be imaged simultaneously in both sense of polarization to obtain full data about the cometary emission. Because the velocity range to be studied is not large, 8 sets of 64 1.5kHz channels would be adequate. Interference excision would be needed, especially at 1612 MHz and 1720 MHz.

2.5 TECHNICAL REQUIREMENTS

Solar system science imposes some of the more demanding constraints on the correlator, total power system, and prime focus systems. All elements of the proposed project will have a significant impact on solar system science, as we now summarize:

- **New Wide-bandwidth receivers:**

  Filling in the frequency coverage with new wide-bandwidth feeds and receivers is extremely important. The 2.4 and 33 GHz bands will significantly augment the VLA's ability to support planetary radar experiments. The VLA will be able to participate in bistatic-mode observations with the newly upgraded 2.4 GHz transmitter at Arecibo, and with a new 30 GHz transmitter at Goldstone. The completion of the 40–50 GHz system will be particularly important for probing the outer layers of the terrestrial planets. The increased continuum sensitivity will enable much greater numbers of background sources to be exploited as probes of the IPM.

- **Frequency agility:**

  To take advantage of the wide bandwidth ratios for solar imaging experiments, we require the ability to re-tune and re-establish phase-lock on timescales < 1 sec. In addition, at least one dichroic system is desirable, pairing the 2.4 GHz/8.4 GHz bands or the 4.9 GHz/15 GHz bands, for example.

- **A wide-band UHF feed:**

  An exciting prospect for solar physics is performing broadband imaging spectroscopy of solar radio bursts over roughly an octave of bandwidth: e.g., 300-600 MHz. To do so requires a broadband feed located at the prime focus. For solar observations, the feed does not need to be high performance.

- **A robust total power system**

  A robust total power system is required for both solar and planetary radar observations. The demands are not stringent for the planetary radar case. They are quite demanding for the solar case, however. During solar flares T_{sys} may increase by orders of magnitude over a timescale of seconds. Therefore an accurate, linear (over a dynamic range of 30 dB), and fast (0.1 s) total power system is needed. A robust total power system is also needed in support of a super-compact array configuration (E configuration), which will be used extensively for mosaicing.

- **A new correlator**

  A new correlator is required to process broadband continuum signals, to support an enhanced spectral line capability, and to support more flexible observing modes. In the case of solar observations, a new correlator is needed in support of broadband imaging spectroscopy. Transient bursts occur on timescales of several 10s of ms over relative bandwidths $\delta\nu/\nu$ of

$\gtrsim 1\%$. Imaging with 128 or 256 channels with a time resolution of, e.g., 20 ms, produces an enormous number of baseline-channels per second ($> 2\times10^6$!) if the full array is employed. It is anticipated that a subarray of perhaps 9-10 antennas will suffice, in which case the number of baseline-channels per second is reduced by a factor of 8-10. Alternatively, a "burst mode" could be employed wherein only short periods of interest are recorded to a large buffer with full temporal and spectral resolution. It is likely that imaging spectroscopy performed by a subarray of antennas would be complemented by continuum imaging in other bands by the remaining antennas.

In the case of planetary bistatic radar observations, the spectral resolution required to resolve the Doppler-broadened radar signal most objects is 5 Hz. On the other hand, observations over a wide bandwidth are required to obtain an accurate measurement of the baseline due to the thermal source emission. These competing requirements suggest correlator modes which support two spectral line observing modes simultaneously, one with high spectral resolution and the other with coarser resolution.

- **A super-compact array configuration:**

  A super-compact configuration with good surface-brightness sensitivity is needed for the study of large-scale transient solar phenomena (eruptive prominences and CMEs), for the study of comets, and for mosaicing fields of interest at high frequencies.

- **An extended configuration:**

  An extended VLA configuration is highly desirable for the study of planets, minor bodies, and the IPM. Bistatic radar in the S band with the A+ configuration will permit comparisons with similar measurements in the A configuration in the 8.4 GHz band with matched angular resolution. In addition, the A+ configuration would allow the Galilean satellites to be resolved.

Chapter 3

THE MILKY WAY GALAXY

3.1 INTRODUCTION

Galactic radio astronomy spans an extraordinary range of astrophysical phenomena: from protostars and their nurseries to pre-main sequence objects; the full range of main sequence stars—including the winds of O stars, the magnetospheres of the Bp stars, and the coronae of late-type stars; post-main sequence objects such as the red giant stars and systems containing a degenerate object—pulsars, cataclysmic variables, and X-ray binaries; and stars at their life's end—planetary nebulae and supernova remnants. But galactic radio astronomy includes far more than the study of stellar constituents. Of critical importance to understanding the Galactic "ecosystem" and its evolution is the study of ionized, atomic, and molecular gas, of dust, and of Galactic magnetic fields.

The observational problems posed by Galactic radio astronomy are as broad as the range of phenomena under study. Objects include the highly transient (pulsars, flare stars, X-ray transients) to the "static" (H II regions); point-like objects (main sequence stars) to highly extended emission (SNRs, H I emission); purely continuum sources (SNRs) to those requiring a powerful spectrometer (masers, radio recombination lines).

The VLA has addressed many of these observational problems with extraordinary effectiveness over the past 15 years. During this time the field of stellar radio astronomy has come into its own, with roughly 30% of the VLA observing time being devoted to stellar objects at present. The VLA discovered the spectacular complexity of the Galactic Center, superluminal sources in our own galaxy. It has also made many other significant discoveries and contributions in almost every area of Galactic research.

This chapter discusses the many limitations now confronting Galactic observers and explores the impact of the VLA Development Plan in this arena. It shows that, in some areas, we could make major progress with only incremental improvements to the instrument (*e.g.*, completion of the 40-50 GHz band). It also shows that the fully enhanced VLA (*e.g.*, the wide bandwidths combined with the A+ configuration) will open entirely new areas of observational radio astronomy via sensitive high resolution imaging of thermal emission.

3.2 STAR FORMATION

3.2.1 Gravitational Infall

Molecular lines with enhanced blue shifted emission, believed to be indicative of gravitational infall, have recently been detected towards several young low luminosity stars including the well known source B335. However, the infall interpretation of such spectral features is not unique. This is especially true as the circumstellar regions of young stars are probably not the simple, radially collapsing regions which have been assumed when modeling these infall sources. For example, all young stars have powerful stellar winds which have sufficient energy and momentum to alter the structure of the circumstellar regions significantly.

In order to understand the processes at work close to young stars and to investigate whether the observed line asymmetries are indeed due to gravitationally accreting material, detailed studies of the circumstellar material around young stars are necessary. Important aspects of such studies are identifying the precise location of the young stars, sufficiently high spatial resolution to probe the circumstellar regions, high spectral resolution to map the velocity field and the ability to distinguish infall from the effects of outflow. These are all areas in which the enhanced VLA will make new and significant contributions.

An important signature of gravitational infall is that material closest to the central young star will have the highest infall velocities. However, the precise location of young stars is often uncertain. Simultaneous spectral and continuum observations offer the best way to accurately determine the relative location of the central star (traced by its continuum emission) and the circumstellar dense gas (traced by the spectral line emission).

For a 1 $M_\odot$ star, the infall velocity only exceeds 0.5 km s^{-1} within 1800 AU of the star, which corresponds to $4''$ in Orion. The VLA can obtain angular resolutions which well sample such small regions. Obtaining $0.2''$ resolution images of young stars in Taurus ($d = 140$ pc) will probe material within 28 AU of the central star.

The 45 GHz band (λ7mm) contains transitions of many molecules which, because of their excitation, provide probes of the material which is infalling but has not been heated by the central young star. Some molecular species, such as CS and SO, trace material which participates in the outflows from young stars or has been disturbed by the outflows. Simultaneous observations of one of these species and a transition of a molecule which does not trace the outflow but traces the cooler infalling circumstellar material, such as H_2CO, HC_3N or C_3H_2, will provide the means of identifying and mapping the properties of the cool infalling material and distinguish it from the outflowing material.

3.2.2 Proto-stellar Disks

Star formation is thought to involve both gravitational infall and subsequent formation and evolution of a proto-stellar disk. The kinematics of a proto-stellar disk can be revealed by the gas motions. Low excitation gas in such a disk can be mapped by emission in the CS J=0$\rightarrow$1 line at 49 GHz. At 15K, the surface where the optical depth is unity in this molecule is likely near 600 AU. For higher temperatures, this surface moves inward, so that, for example, at 40 K it lies at 150 AU. Thus, the CS molecule can provide a good probe of outer disk kinematics. To probe the inner disk one needs a lower opacity transition. This can be obtained with isotopic CS; using the ^{34}S isotope, for example, results in a factor of 10–20 lower optical depth, providing a probe of the inner disk.

CS emission could be imaged in a proto-stellar disk with the VLA with high sensitivity and on arc-second scales; this cannot be easily addressed with other instruments. Cyanoacetylene (HC_3N) has lines across the cm and mm bands which may also be used to probe disk kinematics and chemistry. The λ7mm HC_3N line probes a particularly interesting region, reaching optical depth unity at 2700 AU for a 40 K gas temperature. Although both of these lines may also be imaged at millimeter wavelengths, the derivation of physical conditions in the disk benefits from having images at several transitions available. Also, the phase stability is better at λ7mm than shorter wavelengths, and lower-J transitions will have lower optical depth, providing a probe better suited to high-opacity, inner-regions of the disk. Imaging of spectral lines cannot currently be accomplished in a minimum solar-mass nebula as the expected disk sizes are too small for the existing VLA. The enormous improvement in λ7mm sensitivity offered by the VLA Development Plan could result in good images in a single source transit time.

Formaldehyde (H_2CO) may also be extremely useful for the study of proto-stellar disks. For example, the IRAS4 region of NGC1333 contains two of the youngest stars, or protostars, known, the objects IRAS4A and IRAS4B. Both still possess the massive disks which signal ongoing accretion, as well as their infalling (outer) envelopes and bipolar outflows. Recent observations of several millimeter-wave transitions as well as VLA ammonia images allow us to estimate the observability of the proto-stellar disks in the system. The ortho-formaldehyde column density in the disk appears to be about $N_{\rm Tot}(\text{o-}H_2CO) = 6 \times 10^{13}\text{cm}^{-2}$ at a density of about $1 \times 10^6 H_2\text{cm}^{-3}$. The warmer source 4A appears to have a disk temperature of about 250 K, embedded in a less kinematically active core of kinetic temperature about 100 K. In source 4B the disk appears cooler, about 85 K, while the envelope temperature is lower but poorly determined. The dust blackbody temperatures of the two sources are 37 K and 27 K, respectively. Under these conditions, a plot of line intensity against the upper J quantum number peaks around J=3 or J=4 for the K-doublet lines we are discussing. The size of the disk is on the order of 2000 AU or less, necessitating arc-second resolution. The brightness temperature of the λ2cm formaldehyde line will be a few K, completely beyond the reach of the VLA in any configuration which will resolve the disk. The 48 GHz line should have a brightness temperature perhaps 50% higher, however, and could be imaged in a single transit by the VLA 45 GHz system once it has been installed on all antennas. The 29 GHz line affords similar possibilities. These observability estimates should apply to a large number of forming star systems with proto-stellar disks.

3.2.3 Proto-planetary disks

Young stars are expected to be surrounded by proto-planetary disks, flattened structures of gas and dust from which planets form. In the optical, disks such as that observed with the Hubble Space Telescope in HH30 can only be observed in silhouette against bright nebulae since they are totally opaque to optical photons. The enhanced VLA, however, will not only provide three times better angular resolution than the HST, but will be able to study the inner parts of these disks which are obscured at optical wavelengths. In particular, the expanded VLA is perhaps the only instrument capable of observing the inner few AU of the disk, because the dust present in these objects is optically thick for shorter wavelengths, and thus observations at these wavelengths will "see" only the outer parts of the disk. The enhanced VLA may be the best instrument for penetrating all the way down to the region where planet formation occurs.

In the earliest stages of evolution of low mass stars, we expect material to accrete through a disk on size scales of 100 AU, which can be imaged with the VLA at λ7mm. Images at shorter wavelengths will reach high optical depths too quickly for viewing the critical inner region. A similar argument holds for proto-planetary disks, though here the total mass might be two orders of magnitude less for a minimum solar mass nebula. As a result, optical depth unity at λ7mm occurs at 0".05, a scale which the current VLA can just start to resolve. However, one should be be able to image sufficiently bright sources with the expanded VLA on longer baselines.

The enhanced VLA will be able to explore gas kinematics in proto-planetary and proto-stellar disks with spatial resolution currently impossible with other instruments. Consider a constant density sphere filled with gas and dust of standard abundance ratios. Such a sphere will have a optical depth of unity (due largely to dust) at λ7mm at a radius $\sim$ 50 AU when it contains 1 $M_\odot$ of material. This scale corresponds to $0.3''$ for objects in the Ophiuchus cloud. Thus, images in the 45 GHz band with sub-arc-second resolution of such an object should reveal processes occurring on solar system scales. At λ3mm, an optical depth of unity would occur for the same object at a radius of several hundred AU and the critical inner region would be obscured from view!

Present estimates suggest that within 200 pc of the Sun there are about 100 proto-planetary disks with total flux densities of order order of 1 mJy at λ7mm. The disks are expected to have diameters of about 100 AU ($0.5''$ at 200 pc). In the A configuration an angular resolution of $0.05''$ can be achieved in the 45 GHz band, equivalent to a dimension of 10 AU. Within a beam of $0.05''$, a flux density of $\sim$ 0.1 mJy/beam is expected.

Completion of the 40–50 GHz system will provide a factor of 36 improvement over the present 9 antenna system (a factor of 3 for all 27 antennas, 2 from improved aperture efficiency, 3 from a total bandwidth of 2 GHz, and 2 from better receivers). In observing time, this represents an improvement of 1300! For example, in a 12-hour on-source integration, the VLA will achieve an rms noise of 5 μJy/beam (compared to 0.2 mJy/beam currently achievable), making it possible to image the disks with a signal-to-noise ratio of 20 in this time period. At 40–50 GHz and with the largest VLA configuration, a technique to correct for atmospheric phase noise becomes imperative. Using any nearby masers as a phase reference may require simultaneous observations with two different receiver systems. Alternatives such as fast switching or accurate total power measurements should be explored to provide phase stability.

3.3 MASSIVE STAR FORMING REGIONS

Massive, deeply embedded stars are among the youngest stars that can be observed. These regions are essentially "mini-star burst galaxies" and their study should add greatly to the understanding of the star-burst phenomenon in luminous galaxies. Recently a significant number of hyper-compact H II regions, i.e. H II regions with extremely high emission measures and extremely small spatial sizes ($<$ a few 1000 AU) have been observed. Some of these hyper-compact H II regions are unresolved or only marginally resolved even in the larger configurations at higher VLA frequencies. These regions may include powerful stellar winds and could be dynamically or magnetically confined Stromgren spheres. Hyper-compact H II regions are quite weak radio sources, but increase in strength at higher frequencies. We would like to spatially resolve these H II regions, as well as to measure the velocities of the ionized gas.

The completion of the 45 GHz system, in conjunction with the new data transmission system and correlator for much higher bandwidth performance will dramatically improve the continuum sensitivity available and allow detailed study of such sources. In addition, a further increase in angular resolution provided by the A+ configuration will allow us to probe both the radio continuum and line emission of hyper-compact H II regions on astrophysically interesting scales. Since the line-to-continuum ratio for radio recombination lines (RRLs) increases with frequency, the observation of RRLs in the 45 GHz band will be one of the best ways of determining the kinematics of the ionized gas. For example, a hyper-compact H II region with a total flux density of 5 mJy at 15 GHz and with spectral index of 1 would have a recombination line detectable in the 45 GHz band at a signal-to-noise ratio of 10:1 with 4 km s^{-1} velocity resolution with the expanded VLA in one transit in most cases. Such a line is completely undetectable with the present system at any wavelength with reasonable observing times. With flexible steering of several IFs within the band, observations of a number of different recombination lines could be observed and averaged together to further improve the signal-to-noise ratio.

As hyper-compact H II regions evolve, they should be seen as ultra-compact and compact

H II regions on time scales of order 10^3 to 10^5 years. These are complex sources, often displaying cometary or jet-like extensions and hosting a variety of associated molecular masers. Most interferometric observations of ultra-compact H II regions have lacked the sensitivity to any associated low surface brightness components and large spatial scales to image any such associated structure well. Images of a number of regions from multi-configuration VLA data show remarkably complex structures, but even these observations are limited by u-v coverage on the shortest and longest baselines. The increased surface brightness sensitivity afforded by the proposed E configuration, and the increased angular resolution of the A+ configuration, would aid immensely in imaging the structure of these sources.

Recent VLA data have revealed a synchrotron emitting source at the center of expansion of the H_2O masers in the massive-star forming region W3OH. The synchrotron emission appears elongated in the same direction as the H_2O masers and thus is almost certainly involved with their acceleration. Synchrotron emission implies a population of ultra-relativistic electrons, and strong shocks may be needed to accelerate these electrons. The nature of the central source powering the system is unclear: one possibility is a late O-type star with a fast (1000 km s^{-1}) stellar wind. The synchrotron source is weak ($\sim$ 1 mJy at 5 GHz) and is marginally resolved along its major axis (and unresolved along its minor axis) at all wavelengths with the VLA in the A-configuration. Longer baselines (the A+ configuration) are needed to characterize this source, or any others that may resemble it in other star-forming regions. Other instruments, such as MERLIN or the VLBA will lack the combination of sensitivity and angular resolution needed to study such objects.

3.4 PMS AND MS STARS

The chief limitation on observational stellar radio astrophysics is sensitivity. Consequently, one of the most important elements of the VLA Development Plan for observing main sequence and pre-main sequence stars is the order–of–magnitude improvement in sensitivity afforded by the improved receivers and greater bandwidth. Several hundred stellar radio sources are now known. The upgrade in VLA continuum sensitivity will increase this number by over an order of magnitude. This fact is highlighted in Fig. 3.1, which shows the log(N)–log(S) curve for radio-detected stars. The figure shows the number density per mJy of detected stars listed in the literature. The data have not been normalized per unit area on the sky. Although the counts will be reasonably complete over the whole sky at Jy levels, at low flux densities, the counts must significantly underestimate the true areal density of radio stars. Despite this fact, the number of radio detected stars rises very rapidly as flux density decreases. Sensitivity at the μJy level has the potential to increase the number of radio-detected stars from the current value of a few hundred to thousands or, perhaps, tens of thousands. This phenomenal increase would revolutionize the field of stellar radio astronomy. New classes of radio stars, and previously unknown phenomena relating to stellar radio emission are almost certain to be discovered.

A major focus of modern stellar physics is the comparison of characteristics for whole populations of stars, to separate the effects of such properties as age, rotation, metallicity and evolution on the observed stellar properties, and thereby to provide benchmarks for stellar evolution and stellar dynamo models. Radio observers have been unable to participate in this comparison, because we have lacked the sensitivity to detecting most members of any given population. Except in a few cases, we do not have a representative sample of detections of a class of stars. The few exceptions are classes with a large number of very nearby members, *e.g.*, the RS CVn binary systems. With current sensitivity limits, the radio properties are measurable only for the few brightest members of a given stellar class. One of the greatest impacts the enhanced VLA will have on stellar radio research is that the enormous improvements in instrumental sensitivity will allow the radio-emitting properties of whole stellar populations to be determined. Examples of stellar populations which

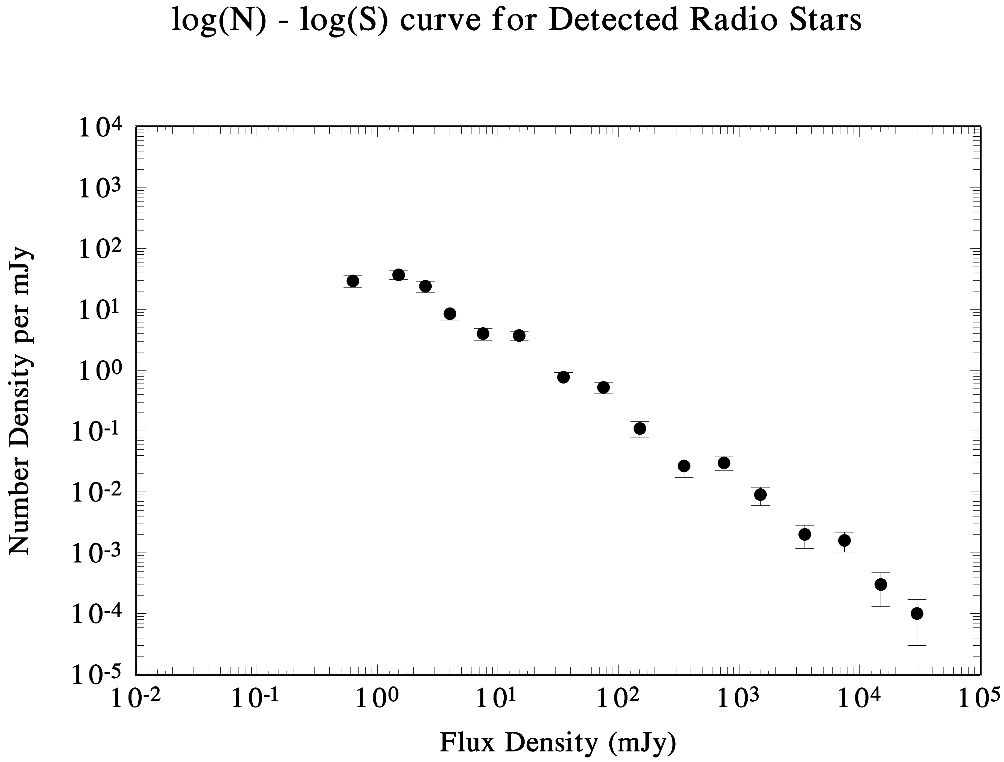


Figure 3.1: The log$N$–log$S$ curve for radio-detected stars.

require improved sensitivity for a proper radio census are:

- Pre–main–sequence stars in star–forming regions: Low–mass stars at the the ages of the Taurus, Ophiuchus and Orion star–forming regions are prodigious continuum radio sources, but the distance of these stars makes them barely detectable by the current VLA. An important example is the class of stars known as classical T Tauri stars (the prototypical low–mass stars descending to the main sequence from birth): a small number of stars in this class have been detected in large surveys. Their radio emission is apparently free–free, and is associated with the outflows which appear to be an essential aspect of star formation and disk accretion. Yet so few have been detected that it is difficult to determine what influences control the level of emission because we cannot carry out meaningful correlations with other observed stellar properties.

- Open stellar clusters: Open clusters provide snapshots stellar activity across a range of spectral classes at a similar age. Prominent examples are the Pleiades and α Per clusters at 50 – 70 million years, and the Hyades cluster at 600 million years. Numerous surveys have so far detected only a small number of stars in these clusters, representing just the peak of the radio luminosity function.

- Cataclysmic variables: A very small number of these stars have been detected by the VLA, yet many of them should produce radio emission at a level just below present thresholds. The radio emission is a diagnostic of the very–high–energy particles accelerated in the accretion process in these systems, for which the only other diagnostic is γ–ray emission. However, few systems have been detected in γ–rays, so the enhanced VLA can make an important contribution to the study of acceleration in these systems.

There are many other examples of similar populations important in stellar physics, for which we have only a poor census of radio detections. However, the most exciting advances provided with the more sensitive VLA will be in the area of "thermal" radio stars. There is a large range of stellar phenomena for which free-free emission from thermal plasma has been detected at radio wavelengths, including novae and nova-like variables, stellar jets, stellar wind outflows, circumstellar shells and disks, and, recently, photospheric emission from nearby supergiant stars. Stars in this class generally have radio spectra that rise toward shorter wavelengths.

For a flux density limited sample of radio sources, an increase in sensitivity can be related to an increase in the volume of space sampled. Fig. 3.2 shows the increase in the volume that will be sampled by the expanded VLA compared to the current VLA, as a function of wavelength. Clearly, the most dramatic increase occurs at wavelengths of a few cm or shorter. Also shown are characteristic spectra of broad classes of known radio stars. Circumstellar thermal sources, such as novae, shells and winds, and stellar photospheres which rise in strength steeply toward shorter wavelengths will be detectable to much larger distances than currently possible.

3.5 ACTIVE STARS

Essentially all classes of stars possessing a soft X-ray emitting corona also have members which show transient energetic activity. The activity manifests itself in powerful flares, with individual events releasing $10^2 - 10^5$ times the energy of a strong solar flare. These include the classical flare stars (the UV Cet or dMe stars), the RS CVn binaries, and the pre-main sequence weak-line T Tauri (WTT) stars.

The flares are accompanied by radio bursts. At frequencies $\nu \lesssim 8$ GHz the dMe stars emit bursts of highly circularly polarized coherent radiation with a brightness temperature exceeding 10^{16} K at times. The emission shows a rich variety of structure in both the time and frequency domains. The emission mechanisms have not yet been identified. The RS CVn stars also display broadband, highly circularly polarized, and extremely bright radio bursts at times. Observations to date have been hampered by insufficient spectral coverage and insufficient temporal resolution (which requires high sensitivity).

An exciting possibility is to exploit the broadband spectral processing capabilities of the new correlator to perform spectroscopic observations of coherent bursts on stars. The motivations for doing so are several: i) to date, spectral observations of stellar radio bursts have only been possible over relative bandwidths $\Delta\nu/\nu \sim$ few percent. The possibility of processing 500 MHz of IF bandwidth instantaneously will allow access to relative bandwidths of several tens of percent, sufficient to resolve structures drifting in the frequency domain (electron beams and MHD shocks); ii) elucidation of the spectral properties of these bursts, of which there are no analogs on the Sun, may allow identification of the relevant emission mechanisms; iii) the extremely high brightness temperatures of these bursts may drive phenomena which are inaccessible to study in other astrophysical objects: *e.g.*, stimulated Compton or Raman scattering.

It should also be pointed out that the incoherent synchrotron and gyrosynchrotron emission from the dMe stars offers a direct diagnostic of physical parameters in the flaring source. Because it is relatively weak (few to a few tens of mJy) the study of incoherent flare emissions would benefit enormously from the high frequency receiver upgrades.

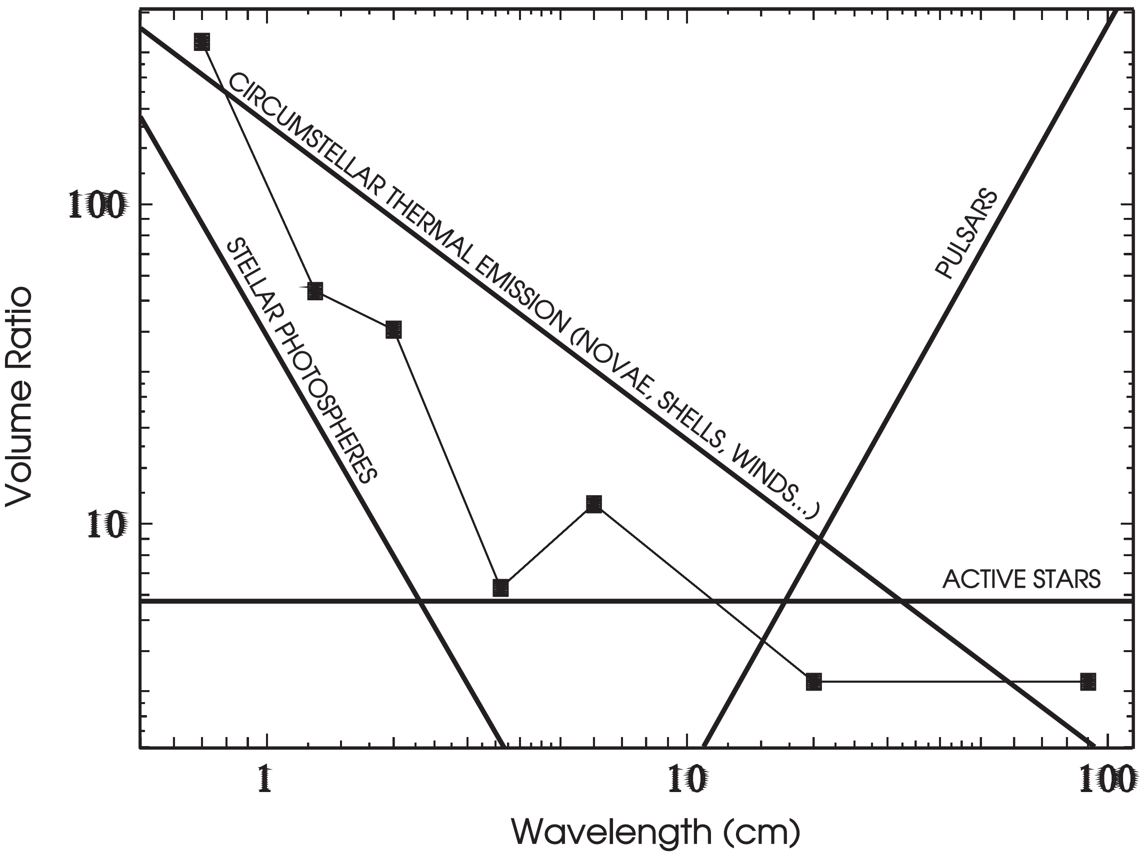


Figure 3.2: The line connecting squares shows the fractional increase in volume, as a function of wavelength, over which a radio source at a given luminosity would be detected by the upgrade in sensitivity. Characteristic radio spectra are shown for four categories of stellar radio sources.

The study of all active stars would benefit from the enhanced frequency coverage and agility proposed in the VLA Development Plan, allowing observers to obtain broad-band spectra of the evolving source over relatively short timescales.

3.6 STELLAR ASTROMETRY

Determination of distances is a fundamental problem in investigations of objects within our galaxy. Spectroscopic or kinematic distances have a high degree of uncertainty, and that uncertainty is generally propagated through to yield even higher uncertainties in astrophysical properties. The large increase in the number of stellar detections promised by the upgrade in sensitivity, coupled with the factor of 7 improvement in the resolving power of the A+ configuration, raises the possibility of carrying out stellar astrometry on a large number of radio stars with sub-milli-arc-second accuracy. Astrometric accuracy at this level would enable accurate parallax measurements out to distances of a large fraction of a kpc. It would also allow the direct measurement of binary motions for nearby non-thermal radio binaries such as RS CVn and Algol systems, and weak thermal emitters such as Be star binaries. Such measurements can yield reliable, independent information on the nature of the binary components and the origin of the radio emission.

One of the chief problems with using stellar radio positions to tie the optical and radio coordinate frames is the binary nature and highly degree of variability of the bright non-thermal radio sources for which accurate radio astrometry is currently available. Thermal emission from the photospheres and winds of single stars is quasi-steady state and centered on the position of the star. These objects are ideally suited for matching optical and radio astrometry. Combined with the observations of bright stars from the *Hipparcos* mission, radio astrometric positions for a large number of thermal emitting, single stars will provide an extensive grid of accurate measurements to tie the optical and radio reference frames with milli-arc-second precision.

3.7 IMAGING THERMAL EMISSION

The combination of the upgrade in sensitivity and the increased angular resolution provided by the A+ configuration opens an extremely exciting area of investigation that cannot be exploited by any other existing or planned instrument – milli-arc-second resolution imaging of thermal radio emission. This capability is placed in context in the angular size versus brightness temperature plot in Fig. 3.3. The two diagonal dashed lines in the figure show the brightness temperatures required to produce flux densities of 100 mJy and 1 mJy within a given angular radius. Curves for the most powerful interferometric arrays characterize their maximum resolution (horizontal portion) and maximum sensitivity (diagonal portion). For a source with a given angular radius and brightness temperature to be *resolved* by an array (and therefore imaged), it must lie above the curve. It is an interesting astrophysical result that at a brightness temperature of a few $\times10^4$ K, radio sources can be broadly divided into non-thermal and thermal. Photo-ionized, nebular sources of thermal radio emission generally have equilibrium, kinetic temperatures of a few $\times10^4$ K. Hence, compact nebular radio sources have brightness temperatures at this value or lower. Photospheric emission from stars, which is optically-thick at kinetic temperatures of $10^3 - 10^5$ K, straddle this 10^4 K boundary. Figure 3 shows the location of the stellar main sequence and giant branches for stars at a distance of 1 kpc.

It is clear from the diagram that, with current arrays, imaging at milli-arc-second resolution is restricted to high brightness temperature, non-thermal, radio sources. For brightness temperatures just over 10^4 K, the MERLIN array provides images a resolution of tens of milli-arc-seconds, however, as brightness temperature drop below this value, the minimum angular dimension over which detectable flux can be obtained increases rapidly. Consequently, imaging at milli-arc-second resolution of the entire class of thermal-emitting radio sources is an area of astrophysical investigation that has yet to be exploited. To access this area requires order-of-magnitude improvements in both sensitivity *and* resolving power. The A+ configuration, in combination with the enormous improvements in sensitivity, will provide that facility. The new region of observational parameter space that would be accessible to imaging by the A+ configuration is illustrated graphically by the shaded region in figure 3. This region encompasses a wealth of phenomena in stellar astrophysics that have hitherto been revealed only as "point sources" of radio emission.

Angular resolution of a few milli-arc-seconds corresponds to a linear dimension of a few AU at a distance of one kpc. This distance is typical of the binary separation of semi-detached interacting binaries containing giant stars, such as symbiotic stars and recurrent novae. Other examples of thermal radio radio sources generated or affected by phenomena on AU scales are the winds and circumstellar environments of early-type stars and the very early stages of novae outbursts. At current resolving power, imaging investigations of these types of objects have been largely constrained to examination of ejected material that has propagated to large distance from the point of origin before becoming resolved. The A+ configuration will finally allow imaging of thermal radio emission on the scale of the interaction that gives rise to ejecta. Fig. 3.4 shows the maximum distance to which these and other types of object would be resolved by both the current

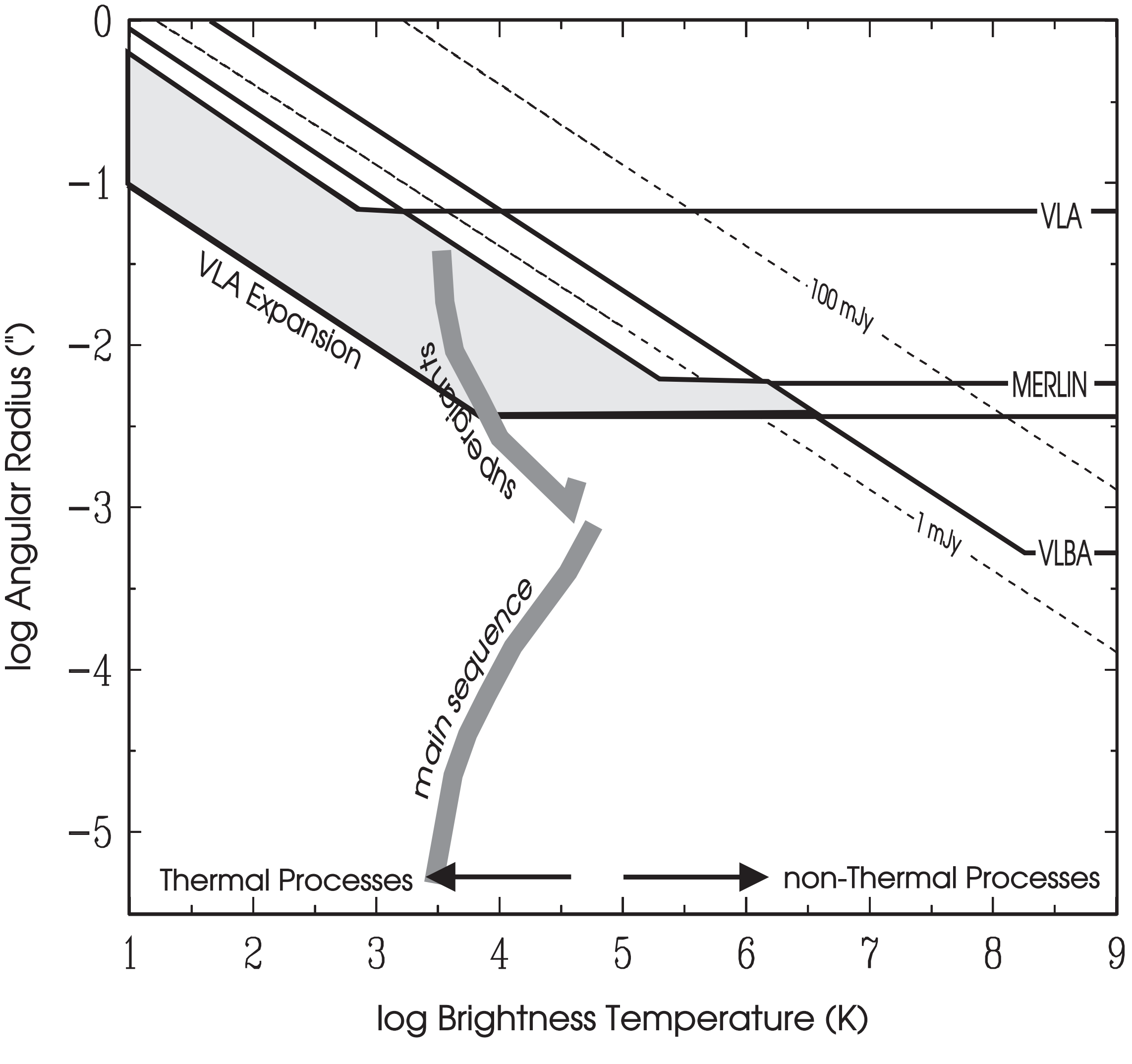


Figure 3.3: Brightness temperature and angular size regimes accessible to imaging by interferometer arrays. The previously inaccessible region that will be opened up by an expanded VLA with the upgrade in sensitivity is shown by the shaded area.

and the A+ configuration. For the current VLA, typical distances range from a few tens to a few hundred parsec. Unfortunately, the space density of these objects is sufficiently low that there are essentially no examples within this resolvable distance. For the A+ configuration, the resolvable distances increase to a large fraction of a kpc to several kpc. Red supergiant photospheres can be resolvable to beyond a kpc, the binary separation of 'D' type symbiotic stars and the very early stages of nova ejections can be resolved out to several kpc, and the circumstellar disks of Be stars out to several hundred pc. At these distances, significant populations of all of these types of sources can be probed on AU and smaller scales for the first time.

Dimensions of order 1 AU have crossing time of order 1 yr for velocities of 10's of km s^{-1}. Hence, milli-arc-second resolving power will allow direct measurement of the angular expansion rate of slowly expanding objects such as compact planetary nebulae and wind interaction shells in the ISM. Combined with spectroscopic data, such measurements can provide accurate estimates of distance for a significant population of objects.

3.8 CIRCUMSTELLAR MASERS

Late-type giant and supergiant stars show maser emission in molecular transitions of hydroxyl, water, and silicon monoxide. These transitions are found at frequencies ranging from 1.6 GHz all the way to 43 GHz. The molecules are found in the circumstellar envelope produced by mass loss from the dying star. The masers appear in a somewhat hierarchical distribution from the central star. Hydroxyl masers are found far out in the shell, and the silicon monoxide masers are found quite close in to the photosphere; water masers are usually found somewhere in between. Since these *are* masers, they are bright and small, thus serving as excellent tracers of the dynamics of the circumstellar shell. These masers are similar in character to interstellar masers, but are usually somewhat weaker, and the maser "spot" sizes are somewhat larger than those of interstellar masers. Much work has been done on these sources using both connected-element and VLB interferometers, giving a reasonably well defined picture of the structures of circumstellar shells.

But there is much more to be done, and the enhanced VLA can contribute substantially to understanding of such masers in circumstellar shells. Much of the science would be dependent upon filling the VLA/VLBA "gap" (see below), but first we address a few studies which could be done without that the VLA Expansion. One example is the detection of the photosphere in the radio continuum by phase referencing to the masers. High frequencies (the 22.5, 33, 45 GHz bands) maximize the sensitivity to the continuum since the emission is thermal (see figure 2). The H_2O masers at 22 GHz, and SiO masers at 43 GHz allow tracking of the phase, removing the effects of phase distortion from the Earth's atmosphere and thereby allowing the expected rms noise to be reached. An upgrade of the 22.5 GHz receivers, with a large continuum bandwidth will allow a factor of 10 improvement in the continuum sensitivity. This limit can be reached by phase referencing to the maser emission. This technique has been used successfully for studies of a few stars, but the Ultra-Sensitive Array will allow many more stellar photospheres to be detected, mapped, and placed within the distribution of masers. The same technique could be used in the 45 GHz band, and outfitting all of the antennas, coupled with large continuum bandwidths, will allow the detection and mapping of the same photospheres at this frequency. Using the frequency agility of the VLA will allow relative position measurements of the H_2O , SiO, and the photospheric emission. Another example of an observation that could be made with the Ultra-Sensitive Array is astrometric observations of the SiO and H_2O masers. Having the whole VLA operating at 45 GHz will allow much improved astrometry of the SiO masers. For the 22.5 GHz band, upgrading the sensitivity of the receivers will allow more, and closer, calibration sources to be used. A final possibility that takes advantage of the frequency coverage is observing excited states of OH (at 5 GHz and 6 GHz) and sensitive searches for other maser lines (e.g. methanol) in these circumstellar

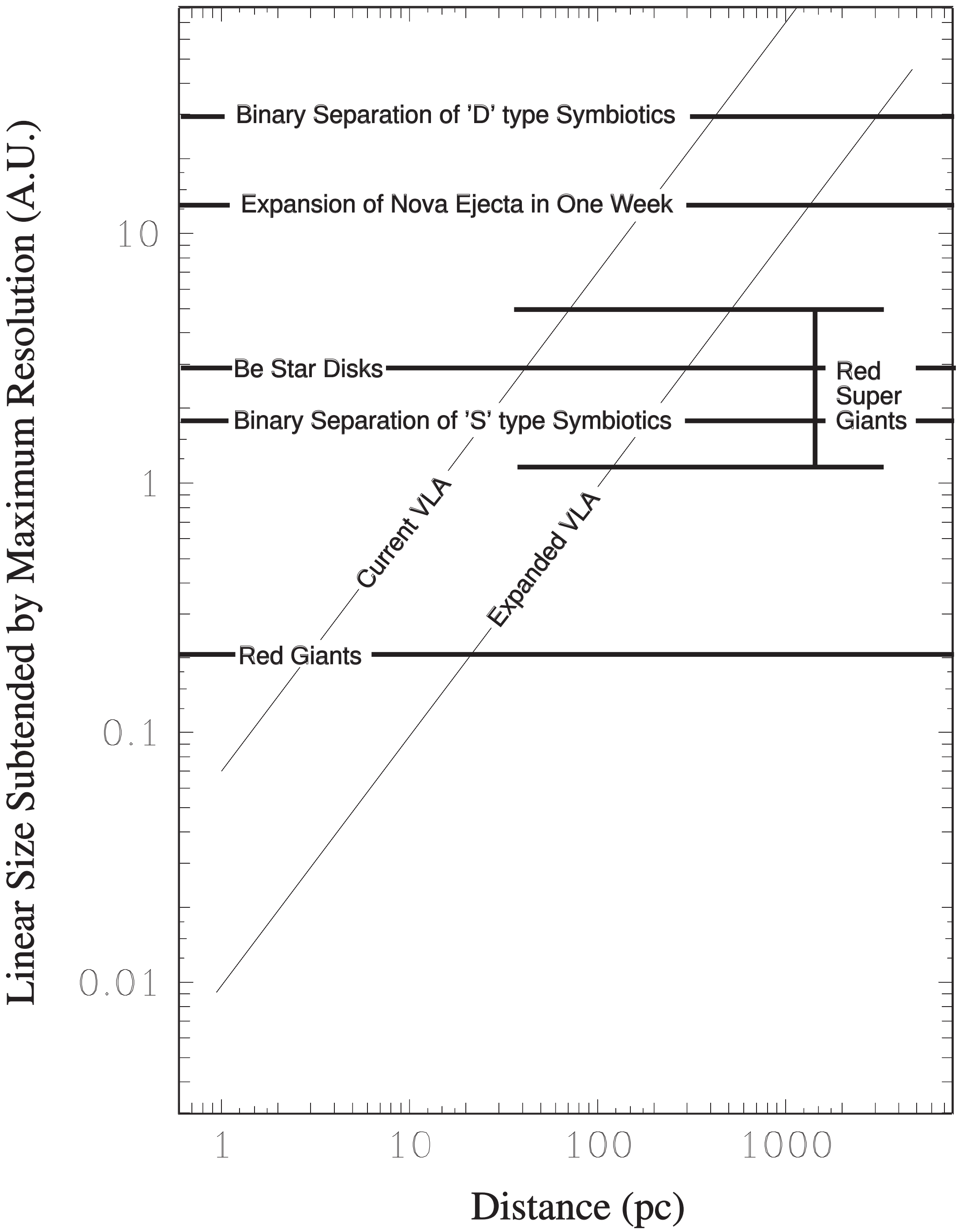


Figure 3.4: The resolving power of the current and A+ configuration compared to the linear dimensions of several known, thermal radio emitting astrophysical phenomena.

shells.

The expansion to the A+ configuration opens up a large range of projects which would enhance our understanding of the dynamics and structure of the shell. VLBI observations of SiO masers at 43 GHz using the VLBA show clear "ring" structures formed from the maps of SiO maser spots. However, the flux density obtained from such high resolution observations is $\approx 50\%$ that obtained from single-dish observations. Thus half the flux density must be found on scales larger than those corresponding to the shortest projected baseline from the VLBI observations. A recent lunar occultation experiment found the missing flux for one source—R Leo—on roughly the scale of the "ring" itself. Thus the baselines between the VLA A configuration and the VLBA are optimal for probing these structures. Another example of the use of the A+ configuration is the polarization observations of OH in the far reaches of the circumstellar shell. The $1''$ resolution of the VLA in the A configuration just barely resolves the shell structures but VLBI data resolve most of the larger scale structure. Even with the A configuration observations, the spectral resolution of the current correlator is too coarse (the best that can be done at λ18cm is 0.5 km s^{-1}, when using full Stokes' polarimetry). We need both the VLA/VLBA extension and higher spectral resolution (at least 0.1 km s^{-1}) to resolve the maser emission spectrally and spatially. Polarization observations throughout the circumstellar shell are important because they can give significant information about magnetic fields and/or the maser process itself.

3.9 RADIO RECOMBINATION LINES

Radio recombination lines (RRLs) in ultra-compact HII Regions have intrinsic widths (FWHM) of about 20 to 50 km s^{-1}. However, if there are significant bulk motions of the ionized gas, the lines may be 80 km s^{-1} wide (*e.g.*, G5.89-0.39). Electron pressure broadening can be significant at frequencies below about 8 GHz, and the line wings of the Voigt profile can extend to 200 km s^{-1} or more. Thus, a total bandwidth of over 300 km s^{-1} is necessary to provide minimal spectral baseline, to determine the line profile, and to measure the continuum level. The line-to-continuum ratio is a critical parameter in any model of RRL emission and it is important to measure the continuum under the same conditions as the line.

Every H line is accompanied by the corresponding He, C and X lines which are spaced at 121 km s^{-1} and 150 km s^{-1} from the H line (due to the differences in their atomic weights). The He line is typically 10% the intensity of the H line. The C line, is weaker still and much more narrow ($<$ 10 km s^{-1} FWHM). All of the lines provide important information about the physical conditions of the ionized gas and the gas excitation and dynamics. The He line yields the He abundance which is an important diagnostic of the chemical evolution of the Galaxy. The C line is a new way to probe the excitation of photodissociation regions around the HII regions of high and intermediate mass stars. It is not possible to cover all these lines in one band with the present correlator. Ideally one would like to cover a velocity range of 400–500 km s^{-1}. At λ7mm this requires a spectral line band width of $\sim$ 70 MHz. For sensitivity one would like to obtain the RCP and LCP data simultaneously. To resolve the narrow C line a channel spacing of $\leq$1 km s^{-1} is needed. Thus, more than 500 channels are needed over an approximately 70 MHz band with two polarizations.

Very broad ($>$ 250 km s^{-1}) and in some cases quite asymmetric RRLs have been observed from ultra-compact HII regions. These observations, which must be made at the highest VLA frequencies where the HII regions are optically thin, have been limited in several respects. First, in order to measure the continuum level, very large bandwidths are required. The current (recirculating) correlator severely limits the number of available channels when large bandwidths are used. Additionally, high spectral resolution is required to resolve lines which may be blended. Secondly, as discussed above, a large portion of the continuum emission from ultra-compact HII regions is very weak and extended, thus producing very weak RRL emission. Increased continuum sensitivity and increased surface brightness sensitivity would allow us to determine the kinematics of the ionized gas over the entire extent of the H II regions.

3.10 MOLECULAR LINES

In addition to the complex ionized (and non-thermal) sources just discussed, regions of massive star formation are rich in molecular emissions. The NH_3 molecule is one of the most useful for the study of high density molecular material, because of series of inversion transitions just above 23 GHz. These transitions have hyperfine components and, thus, allow direct estimates of density and clumping (filling factor).

For example, the NH_3 (2→2) inversion transition has five components: a main line, two inner satellites separated by 116.55 km s^{-1}, and two outer satellites 125.7 km s^{-1} from the main line. To resolve the lines, sometimes as narrow as 0.25 km s^{-1}, a channel separation of 0.05 km s^{-1} is desirable. To allow for enough channels outside the outer satellites in order to measure the baseline, a total bandwidth of 100 km s^{-1} (8 MHz) needed with about 2000 channels. If the source has gas motions which are of order 16 km s^{-1}, every one of these channels could contain line signal. (If the motions are more typically 5 km s^{-1} or less, some savings could be had by positioning independent groups of channels on each of the lines in which case only 1000 channels are necessary.) For greater sensitivity, one would like to obtain the LCP and RCP data simultaneously. Using the present correlator, most observers are forced to ignore the outer satellites (although they can help constrain LTE models and provide and independent column density estimate). Typically only the main line and the inner satellites are observed in a 3.125 MHz band with 16 or 32 channels. The main line and the satellites are often blended in the channels which have only 1.25 km s^{-1} resolution.

A new broadband data transmission system and correlator are needed to make a major advance and provide adequate spectral resolution and capabilities to do multiple lines simultaneously. For example, in the 22.5 GHz band, one could make T_k and density maps using the many NH_3 transitions. For hot cores near H II regions one would like to use the (1→1) and (2→2) transitions to get the extended, lower temperature structures; use the (4→4) and (5→5) transitions for moderate temperatures, and higher metastable line to get the higher density, hotter features; also the non-metastable lines such as the (2→1) can be used to study the highest densities ($N \gg 10^5$); and finally the (3→3) and (6→6) ortho lines often mase. Clearly at least 4, and preferably 8, independent channels would be desirable. The frequency range from (1→1) to (6→6) is 23–25 GHz and spectral channels of width of about 8 MHz per line and 8 kHz spectral resolution. Also, a simultaneously, broad-band continuum measurement would provide valuable complementary information regarding the physical setting and sources of excitation.

The CS molecule has its fundamental J=1→0 transition at 49 GHz, in the new 40–50 GHz system of the VLA. Recent observations of the IRc2 region in Orion using the existing 45 GHz system have approximately twice the spatial resolution of any existing image made with a thermally excited molecular line. The outflow of IRc2 is evident as well as a velocity gradient running along the length of the Orion molecular ridge. The enhanced VLA could produce an image with approximately 30 times better sensitivity, making it possible to map the dynamics of the outflow as traced by the weak emission in the line wings.

Maser observations, whether OH at λ18cm or CH_3OH at λ7mm, are some of the most demanding spectral line projects. High spectral resolution is required to measure the very narrow lines (< 0.1 km s^{-1}), a wide velocity range is needed because the masers in star forming regions can be present over a wide range in velocity, wide fields may need to be imaged because star formation is often highly clustered, and polarization measurements are needed if one is trying to use the Zeeman effect to measure the in situ magnetic field. One may wish to cover 40–80 km s^{-1} with channels as narrow as 0.1 (even less for Zeeman experiments). Thus 800–1000 channels are needed with circular polarization information. Masers are important sign posts of new star formation, they a valuable probes of the interstellar gas dynamics, they are used in proper motions studies to determine the distances, and they are valuable tools for self-calibration of continuum or other line measurements because they are bright, unresolved point sources.

There are additional molecules of interest. Massive organic molecules (*e.g.*, carbon chains and possible rings), are building blocks of molecules crucial to formation of living organisms. There are reports of mm-wavelength detection of amino acids. These observations were not possible with single dishes owing to line crowding, but were successful with an interferometer. Thus, large molecules with transitions at centimeter -wavelengths are probably best detected with the VLA, over (say) the Green Bank Telescope, because of the excellent spectral baselines achieved with an interferometer and the higher duty cycle on-source. Also, since the VLA antennas are much smaller than a large single dish such as the Green Bank Telescope, the increase in noise from the source (e.g., Sgr B2, Cas A) is much smaller for the VLA. The combination of all these advantages (for the enhanced VLA versus the Green Bank Telescope we estimate factors of 1.5 for collecting area, 1.5 for increased duty cycle, and a factor of order 3 (for a 100 Jy source) from system temperatures) yields a sensitivity increase of 7, or an integration time of 50—favoring the VLA! The wider field of view at the VLA might also be valuable if the position of the line emission/absorption is not precisely known.

Formaldehyde has been a staple molecule for centimeter-wavelength telescopes for many years. Unfortunately, only two lines have been available for study—at λ6cm and at λ2cm. These lines are affected by the well known excitation anomaly which causes them to be seen in absorption against the 2.7K background over much of a cloud's extent. Fortunately, the VLA will make available several very interesting new transitions with completion of the 45 GHz system. Formaldehyde may turn out to be the "molecule of choice" for probing physical conditions in clouds with the VLA. In addition to the λ6cm and λ2cm lines, the 3(1,2)$\rightarrow$3(1,3) line at 28.975 GHz, and the 4(1,3)$\rightarrow$4(1,4) line at 48.3 GHz could be available on the VLA. These lines are very useful densitometers. Mangum (1990) noted in his dissertation that these K-doublet transitions have a spatial density filter built into their excitation; for densities below 10^5 the formaldehyde lines are in absorption for J of 4 or below, while for densities above this value all are in emission. At J $\geq$ 5, all lines will be in emission where the excitation is sufficiently robust. Mangum also showed that formaldehyde is less susceptible to abundance peculiarities than some other molecules, notably ammonia, which render interpretation of the observations difficult. Formaldehyde observations at higher frequencies will provide an excellent densitometer, free from the complex cloud-envelope effects which plague interpretation of lower-lying formaldehyde lines. Formaldehyde has been detected in several external galaxies; the additional higher frequency lines should be detectable in several galaxies with the VLA, providing valuable density information.

3.11 X-RAY TRANSIENTS

In the last 15 years several categories of X-ray binaries and X-ray transients (X-ray "novae") have been studied. They demonstrate a strong need for the A+ configuration to allow sensitive imaging with 5-10 milli-arcsec resolution, and for simultaneous observing with the VLBA to cover size scales from 0.5 milli-arcsec up to a few arcsec. VLBA and VLA observations of the newly discovered relativistic jets in the X-ray transient GRO J1655-40 show both the potential for the study of relativistic, X-ray source jets, and the critical information gap between the VLA and the VLBA. The VLA studies of GRS1915+105 show that it is a similar relativistic jet, with an estimated (but not directly measured) jet velocity of $0.92c$. It shows tantalizing information on the 20 milli-arcsec scales accessible with the VLA: but without the A+ configuration and the VLBA one cannot reach the level of detail seen in GRO J1655-40. The $0.92c$ jets in GRO J1655-40 show structure moving between 54 and 45 milli-arcsec/day that varies from superluminal to subluminal, linearly polarized features, and ejection on both sides of the core. Detailed structures are seen which are some combination of kinematic modulation of the ejecta and physical substructures. These ejecta quickly evolve from size scales of 5-10 milli-arcsec to large scales, then appear resolved out with the VLBA while they are unresolved with the current VLA, and are unseen substructures until they move/expand to the 100 milli-arcsec scales where they are resolved features in high resolution VLA images.

Imaging with the A+ configuration would provide excellent minute-to-minute snapshots that would avoid the need to calibrate VLBA data with models that include the motions of complex sources during the times of observation. In addition, spectral index imaging of 0.1–1$''$ jets requires the A+ configuration; and for the 10—100 milli-arcsec scales, the A+ configuration is essential to get the needed higher frequency images at the right size and brightness sensitivity scale. Without this, astrophysical analysis of detailed structures such as in GRO J1655-40 will be difficult.

GRO J1655-40 and GRS1915+105 are certain candidates for the level of detailed study that is not possible for extragalactic jets. What evidence is there that other X-ray binaries and transients exhibit similar phenomena requiring the A+ configuration or cross-linking the A+ configuration with the VLBA? Both SS433 and Cyg X-3 are known to have continuous or flare-produced jets with speeds of $0.26c$ and $(0.2–0.4)c$, respectively. EVN observations of SS433 have directly shown that jet ejecta have a "brightening" region which extends from the core to about 30 milli-arcsec (for a distance of 5.5 kpc). Until now this is the only case where *in situ* particle acceleration near a "central engine" has been directly observed. On three occasions, Cyg X-3 has been seen to have $0.2–0.4c$ North-South expansion, and it was once imaged as a triplet on size scales of 0.15$''$. The A+ configuration, or inner VLBA elements with the A+ configuration, are the only instruments with the combination of surface brightness sensitivity and resolution to examine the acceleration regions in these relativistic jets.

Six other X-ray transients have been shown to have the sort of decaying, post-flare, synchrotron emission seen in GRO J1655-40: GS2023+338 (V404 Cyg), GS1124-683 ("Nova" Muscae 1991), GS2000+35, A0620-00, Cen X-4 and Aql X-1. The time scale for these events ranges from a few days to a few tens of days. In only two cases was it possible to look at these sources with the VLA A configuration, and they were unresolved; however, this covered very little of the decay events. Some of these events may have been image-able with the A+ configuration, or the VLBA. Without knowing that there are resolved ejecta from VLA or A+ configuration snapshots, such objects are unlikely to get VLBA attention during the critical 1–5 day time scales when they are strongest. (The most important VLBA images of GRO J1655-40 began one day after the peak in the radio light curve and covered the next 10–15 days after two interesting flares.)

About 15 other X-ray binaries are known radio sources. One class, the so-called Z-sources (after their Z-shaped X-ray color-color diagrams) show state changes in which changes in the structure of their accretion disks are followed by state changes in radio and UV emission (Sco X-1, GX17+2, Cyg X-2). A change in a large-scale incoherent synchrotron emission region tens of minutes after an alteration in accretion disk structure requires bulk propagation velocities of the order of $0.1c$ or greater. Since this emission is typically weak (1—30 mJy) the imaging of this ejecta, estimated to be several mas or larger in size, will require the sensitivity of the A+ configuration or the cross-linked VLA+VLBA.

The "great annihilator" 1E1740.7-2941 and GRS1758-258 are both associated with γ-ray sources that are similar to GRO J1655-40 and GRS 1915+105. Both have twin jets on scales from several to tens of arc seconds. Their jets are variable, but neither has had a regular sequence of high resolution imaging to see structure variations in their core and inner jets. They may be similar to the two highly-relativistic jet sources during and after flare events but have only been observed long afterwards, when only surviving large ejecta are present.

It is a mixture of the short time scales of significant motion, expansion, and evolution, and the fact that they quickly achieve angular sizes within the resolution of the VLA/VLBA "gap" that makes the A+ configuration, preferably cross-linked with the VLBA, critical for studying the resolved relativistic jets in the X-ray binary and transient systems in our own galaxy. The detailed spatial and spectral index imaging of these phenomena as a function of time, coupled with γ-ray, X-ray, UV, and optical studies, will provide a level of detailed, evolution-tracing information unattainable for AGN jets.

3.12 SUPERNOVA REMNANTS

The origin of cosmic rays (CRs) has been an outstanding problem in physics since their discovery. There is a strong case to be made for CR production in supernova remnants (SNRs) because: i) maintaining the energy density of CRs requires a supply of energy that can easily be provided by SNRs; ii) relativistic particle acceleration must take place in SNRs because we observe the synchrotron radiation from the electrons; and iii) SNR ejecta are rich in heavy elements as are CRs. However despite the qualitative evidence, CR production and shock acceleration processes in SNRs remain poorly understood. Two observational diagnostics are available which may shed light on this long-standing problem: spectral imaging and integrated spectrum studies.

3.12.1 Spectral Imaging

High-resolution, multi-wavelength, observations are important because the radio spectrum constrains the energy spectrum and spatial distribution of the relativistic particles. The key is to relate measured spectral variations to the dynamical structure of the remnant, since models of particle acceleration in SNRs, either by shocks or by second-order Fermi (stochastic) acceleration in interior turbulence, predict structure in the particle distributions produced. Measured variations must be related to acceleration processes or the energy spectrum of the seed particles. Variations in older SNRs can also be related to compression of CR gas and IS magnetic field.

Only a handful of SNRs can usefully be studied in this way with the current VLA—spatially-resolved studies of the spectral index between 1.4 and and 4.9 GHz have been possible only on a few remnants. Dispersions in spectral index of up to 0.3 have been reported, though other reported variations are less certain. The key limitations in extending the accuracy of these studies to other SNRs have been insufficient surface brightness sensitivity at higher frequencies and insufficient angular resolution at lower frequencies.

Of $\sim$ 130 Galactic SNRs which can be seen with the VLA, the complete structure of only $\sim$ 5–10 can be reliably imaged with the VLA at λ6cm. The E configuration plus total power measurements will increase by more than a factor of 2 the number of SNRs that can be studied at λ6cm. Furthermore some studies could be extended to λ3.6cm for at least several bright shell-type SNRs in addition to Cas A.

Observations at 333 MHz with sufficient sensitivity to trace the variations have only been available recently with the advent of wide field imaging. The range of a factor of 12 from 333 MHz to 4.9 GHz should produce much more robust results, as well as allowing three frequency spectral-index maps to be constructed and cross-checked against one another. However while the present angular resolution at 333 MHz ($6''$ in the A configuration) will be useful for following larger scale variations, observations at $\sim 2''$ resolution with the A+ configuration are required to properly extend scaled array observations from 4.9 and 1.4 GHz to lower frequencies. Completion of the 74 MHz system and its extension to the A+ configuration and inner VLBA antennas would provide yet a further extension of spectral index studies in frequency space. Because cm-wave observations are not sensitive to electron energies associated with particle injection, important aspects of the acceleration mechanism cannot be directly addressed at those wavelengths. Below 100 MHz, the ability to measure the mid-energy range of synchrotron emitting electrons, where injection may be taking place, is greatly improved. There is therefore a real possibility of probing the acceleration process with 74 MHz VLA observations.

Reverse-shock related emission plays an important rôle in young SNRs such as Cas A. X-rays are generated when freely expanding ejecta is heated by the reverse shock. This mechanism has been used to explain the inner components of the concentric double-shell X-ray morphology seen in Tycho and Cas A. However, information on the physical conditions of the unshocked ejecta interior to SNR reverse shocks has been scant, as that cooler material has been largely unobservable. Recent 74 MHz VLA data indicate free-free absorption of low frequency radio emission by ionized gas interior to the reverse shock in Cas A. This provides the first evidence for the inner component of cool, ionized ejecta in Cas A expected by theory. The absorption is manifest as a large, arc-minute scale spectral index flattening. Emission from the back face of the synchrotron emitting radio shell provides the background against which the free-free absorption at 74 MHz is revealed. The present 8 antenna 74 MHz prototype has insufficient sensitivity to extend such studies to other SNRs other than, perhaps, the Crab Nebula. And even here the u-v coverage is so poor that observations over many years must be obtained to achieve adequate u-v coverage, *i.e.*, the system is prohibitively slow. A full 27 antenna system would extend meaningful studies to other SNRs.

3.12.2 Integrated Spectrum Studies

As well as studying the spatial variations of spectra, we may use observations at the lowest ($<$ 100 MHz) frequencies to investigate SNRs and their interaction with the ISM via integrated spectrum studies. Nonlinear models of electron acceleration in shocks predict an electron spectrum flattening with increasing energy in the region 0.1–20 GeV appropriate for electrons emitting at radio wavelengths by the synchrotron mechanism. Some evidence for the corresponding flattening in the integrated radio spectrum has been found in Tycho, Kepler and SN1006, though with large errors.

When combined with higher frequency measurements, flux densities for SNRs that may only be marginally resolved at 74 MHz ($\sim 20''$ for the VLA, $\sim 7''$ for the A+ configuration) may still give a sensitive measure of the integrated radio spectrum. A 74 MHz 27-antenna VLA system providing an rms $<$10 mJy in 12 hrs would give valuable low frequency flux density measurements for SNRs. Previous measurements below 100 MHz for all but the strongest SNRs have large uncertainties because almost all of them were obtained with single dishes and are strongly confused by nearby thermal sources and the Galactic background radiation.

3.13 PULSARS

It is widely held that pulsars are born in the Galactic plane from massive Population I stars ($> 8\ M_\odot$) and that their large scale heights can be attributed to a birth velocity of a few hundred km s^{-1}. Proper motion measurements are the observational support for the inference that pulsars are a high velocity population born in the plane. Such measurements, when used together with the distance and age of a pulsar, give the magnitude and direction of the transverse velocity of the pulsar. Not only does this demonstrate that the majority of pulsars are migrating out of the plane, but in some individual cases it can be used to trace the pulsar back to its origin, be that an OB association and/or a supernova remnant.

The distribution of pulsar velocities is another important area of research. Important questions can be answered on the origin of these velocities (binary disruption and/or random "kicks") simply by knowing the true shape of the distribution. To date, proper motion measurements have been made for less than 15% of the known pulsars, producing a sample which is seriously limited by selection effects (*i.e.*, bright, nearby pulsars). Indeed, attempts to correct for these selection effects have suggested that the mean pulsar velocity may be larger than was commonly thought by a factor of 2–3.

By necessity, astrometric observations have been made at centimeter wavelengths to avoid ionospheric effects. However, as pulsars are steep spectrum ($\simeq \nu^{-1.6}$) objects, observations at λ10–20cm require that we gate the correlator on pulse for increased signal-to-noise ratio. The current small sample of pulsars with proper motion measurements reflects the twin limitations of sensitivity and positional accuracy. The current VLA yields superior sensitivity but is limited in positional accuracy ($\sim$ 10 milli-arcsec/yr). Conversely, the VLBA has excellent positional accuracy but is limited to phase reference observations on the brighter pulsars (>5–10 mJy). The enhanced VLA, particularly the A+ configuration with the wider bandwidth 1.4 GHz system and the new 2.4 GHz system, will greatly increase the number of objects for which we can do accurate astrometry.

The VLA Development Plan benefits pulsar studies in two ways: through improved signal-to-noise ratio and positional accuracy. All IF improvements (receiver, fiber optics and correlator) provide a signal-to-noise increase. The 2.4 GHz receiver and the increased bandwidth of the 1.4 GHz receiver gain a factor of 2 in signal-to-noise. However, the greatest improvements come from the A+ configuration. In the best case we should improve positional accuracy by $\times$20 at 1.4 GHz and at 2.4 GHz. To achieve these improvements for the rapidly rotating and high-dispersion-measure pulsars will require that the new correlator have a frequency dependent gate so that the pulse phase can be accurately tracked across the full available bandwidth.

With the current VLA we can observe the 40 closest and brightest of 700 known pulsars. With the proposed improvements to VLA sensitivity and the A+ configuration we can do sub-milli-arc-second astrometry for mJy pulsars, with which a significant fraction (>30%) of the known pulsar population can be studied. The expected improvements, normalized to our current capabilities with the current VLA at 20 cm, are illustrated graphically in Fig. 3.5. We estimate that the number of pulsars with proper motion measurements would double, and that a trigonometric parallax could be measured for pulsars out to a distance of 1 kpc. Serious investigations of pulsar velocities could begin, unhampered by selection effects.

3.14 LARGE-SCALE STRUCTURE

3.14.1 The Galactic Center

Studies of the Galactic center have provided some important highlights of the first 15 years of VLA research. The Galactic center mini-spiral was discovered at the VLA in 1983. One of the most exciting and unexpected VLA discoveries of the early 1980's was the sensational discovery in 1984 of the linear arcs near Sgr A. The thermal arched filaments and the non-thermal arcs at 0.16° Galactic longitude are two of the most fascinating and enigmatic Galactic objects. At the center of all of this unusual activity is Sgr A*—the nearest AGN—which can be studied with linear resolutions of less than 0.01 pc.

There have been a number of recombination line studies of the thermal gas near the the Galactic center. A study of the H 92α line (λ3.6cm) was carried out in 1993 with an angular resolution of about 1$''$. The velocity range of 450 km s^{-1} was barely sufficient to cover the full range of velocities. In addition there are some portions of the thermal sources that are optically thick at λ3.6cm and thus cannot be imaged. With the enhanced VLA it will be possible to image recombination lines at λ2cm, λ1.3cm and λ0.7cm with a resolution of several arc seconds over the full velocity range

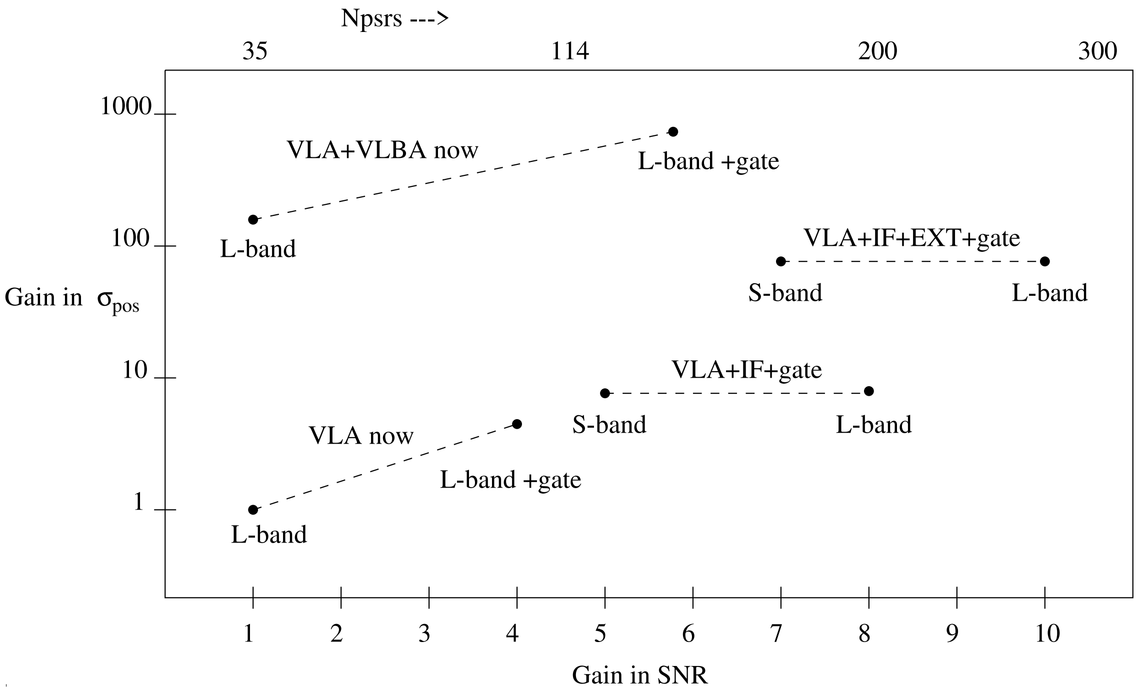


Figure 3.5: A comparison of the relative capabilities of several VLA configurations for pulsar astrometry. Shown are the current VLA and VLA+VLBA capabilities in the 1.4 GHz band, with and without the gate, as well the predicted capabilities of the enhanced VLA, with and without the A+ configuration. The two axes are gain in sensitivity and gain in positional accuracy, and the numbers are gains relative to the current VLA without gating. Displayed above the plot are the number of pulsars available to each configuration.

of 1000 km s^{-1}. The electron temperatures and kinematics of the thermal gas will be determined.

The current VLA correlator limits high frequency observations of the molecular material in the Galactic center region. Both radio recombination line and molecular lines require a velocity coverage of at least 1000 km s^{-1}, which is impossible with the current VLA correlator. The new correlator and improved high frequency receivers (especially λ7mm) will allow mosaicing of the Galactic center region with many simultaneous lines over a large velocity range. It will be possible to determine the physical conditions such as temperature and density over a wide range of linear scales of the gas that appears to be feeding the black hole at the center of the Galaxy.

Scattering of radio waves by thermal electrons along the line of sight distorts the images of OH/IR stars in the Galactic center, as well as of Sgr A*. The scattering has been shown to be asymmetric and to be related to the location with respect to Sgr A. The A+ configuration will be optimal for studying this phenomenon as the OH sizes are often in the range 0.1 to $1''$.

3.14.2 The Galactic Magnetic Field

Most measurements of Zeeman splitting of thermal OH in cloud cores have been done with single dishes. These measurements average over regions of a source where physical conditions probably vary considerably. As highly clumpy substructure is likely, it is not clear what densities are involved. The E configuration would be the ideal instrument to achieve greatly increased angular resolution, compared with most single dishes. (Compared to Arecibo, the VLA offers greatly increased sky coverage, integration time, side-lobe rejection, and spectral baseline stability.)

The Milky Way is known to possess some sort of large scale magnetic field configuration, based largely on analysis of the rotation and emission measures of pulsars. However, recently Zeeman-effect measurements of interstellar OH masers has suggested an additional source of information about the magnetic field of the Milky Way. Magnetic field directions determined from OH masers show large scale structures, largely consistent with those inferred from pulsars. Since magnetic fields measured in regions of OH masers, provide in situ measurements of the field, the information obtained from OH masers is different from that of pulsars, where an integral (of the electron density weighted) magnetic field along the line of sight is obtained. Thus, OH masers provide information complementary to that obtained from pulsars about the magnetic field of the Milky Way.

Interferometric mapping of large numbers of OH masers is needed to make significant progress in this field of study. These observations offer the opportunity to measure magnetic fields in many regions across the Galaxy, and thus to strongly constrain the structure of the magnetic field of the Galaxy. Currently the VLA suffers from limited angular resolution of the A-configuration. Extending baseline coverage to about 500 km would be a major advance, providing the highest sensitivity and angular resolution that can be applied to a large number of (usually weak) sources, many of which are heavily resolved by VLBI observations as the maser spots are often broadened by interstellar scattering.

3.14.3 Galactic Nonthermal Continuum Emission

The WSRT northern sky survey at 330 MHz has detected very large scale polarization structures at low and intermediate Galactic latitudes which are thought to be produced by spatially varying galactic Faraday rotation of the intrinsic polarization of the galactic nonthermal continuum radiation. These polarization features are apparent on spatial scales ranging from $10'$ to several degrees. The detailed study of these features requires total power measurements and large scale mosaicing in total intensity and linear polarization at three frequencies at or below 1.4 GHz. Such a study would provide constraints on the electron density and the magnetic field in the Galaxy, which in turn could be used to produce a specific model of the hot ionized medium phase of the ISM.

A byproduct of the investigation would be a high resolution look at the magnetic field structure, corrected for Faraday rotation, of the Galactic nonthermal continuum, which would provide insight into Galactic dynamics and the interaction between SNR and H II regions and the ISM. A high resolution spectral index study of the Galactic continuum emission would help answer questions about the source of cosmic rays. Comparison of a high resolution continuum image and the FIR emission could shed light on the details behind the very tight FIR-radio-continuum correlation seen in other galaxies.

These projects require the E configuration for high brightness sensitivity and good mosaicing quality, and some additional frequency coverage between 300 MHz and 1.4 GHz.

3.14.4 Galactic H I

The Dwingeloo 25 m telescope has recently surveyed the Galactic H I emission in the northern sky at $30'$ angular resolution and 1 km s^{-1} spectral resolution. The key feature of the Dwingeloo survey is that the spectra have been corrected for stray radiation, which can account for up to half the signal seen at high latitudes. The DRAO interferometer is currently engaged in a survey of the H I in the Galactic plane at $1'$ resolution. However, DRAO is limited to observing only the northern part of the plane.

VLA D configuration mosaics of Galactic H I emission reveal very complicated filaments and structures on all spatial scales. After only a few minutes integration per pointing in the D configuration, the image quality is limited by the effects of the incomplete Fourier plane coverage. This is a strong argument for the E configuration, which has essentially complete Fourier plane coverage in a single snapshot. E configuration mosaicing will permit much higher quality images of the complex H I structure, permitting deeper integrations.

With the VLA E configuration, it will be possible to survey the H I in large parts of the plane rapidly at $3'$ angular resolution and 0.5 km s^{-1} spectral resolution. We know from VLA D configuration Galactic H I imaging that 30-sec snapshots with the VLA E configuration will detect abundant interesting structure. The VLA E configuration would be able to image the complicated H I filaments in only one snapshot. A survey covering one quadrant and $10°$ in Galactic latitude would take only 120 hrs to complete.

A high resolution fully sampled survey of Galactic H I would provide an important database for i) modeling the gas dynamics in the Galaxy; ii) comparison with surveys of molecular gas and detailed modeling of the conversion between atomic and molecular gas in molecular clouds or photodissociation regions; iii) comparison with the features in the radio continuum, possibly allowing determination of the distance to the continuum features if the H I and the continuum are correlated, and iv) detailed interaction between the violent events in the disk, such as SNR, H II regions, and disk blowout events, and the H I .

Chapter 4

EXTRAGALACTIC RESEARCH AND COSMOLOGY

4.1 INTRODUCTION

Extragalactic radio astronomy spans the study of normal stellar phenomena in external galaxies, of the intense, extended ejecta of radio-loud AGNs, and of the gaseous environments of galaxies and clusters of galaxies. Our ability to trace the more radio-luminous phenomena to high redshifts interweaves the study of the evolution of radio sources and their environments with the study of the large-scale structure and evolution of the universe itself. Extragalactic astrophysics and cosmology are thus both mutually entangled and mutually illuminating.

We are now entering an age in extragalactic radio astronomy in which we can detect the normal stellar phenomena (supernovae and their remnants, synchrotron and thermal emissions from disks) in many external galaxies. The gas content of normal galaxies can be studied to redshifts high enough to observe some effects of cosmological evolution directly. The radio-loud populations, and examples of dusty-star-forming galaxies, can be examined out to redshifts at which the universe was only 10% of its present age. This allows direct and dramatic probes of how the observable properties of starbursts, radio jets and lobes depend on cosmological epoch.

We have also uncovered ways to use extragalactic radio sources to probe the environments in groups and clusters of galaxies, through their direct bending and distortions by intergalactic gas, through their Faraday rotations, and through gravitational lensing of distant systems by foreground matter.

The enhanced VLA can make enormous contributions to all these aspects of extragalactic research. In some arenas, such as the study of large-scale jets and lobes formed by radio-loud AGN's, it will allow us to advance to the next level of detail in astrophysical modeling of individual objects—its improved resolution and sensitivity will allow new and critical tests of more realistic models. In others, such as the study of supernovae and their remnants in external galaxies, the sensitivity of the enhanced VLA will give access for the first time to a representative population of the objects. Perhaps most exciting of all are the opportunities that the improved sensitivity, expanded correlator capacity and frequency coverage will give us to observe the effects of cosmological evolution directly in a variety of contexts, ranging from the gaseous content of normal galaxies and galaxy clusters to starbursts and the large-scale sources associated with radio-loud AGN's.

The VLA was originally designed with the needs of extragalactic astronomy very much in mind in terms of defining resolution and sensitivity targets. Its spectacular success in this field of research has by no means "wrapped up" its vital rôle in the study of the distant universe. Rather, it has allowed us to glimpse the even more exciting possibilities that exist for extragalactic science with the more capable instrument that is now being proposed. This Chapter reviews these possibilities.

4.2 NEARBY GALAXIES

4.2.1 Supernovae

Radio studies of supernovae and supernova remnants provide information on stellar evolution, stellar mass loss, particle acceleration mechanisms, energy input to the interstellar medium, and the structure of the ISM. The high sensitivity proposed for high frequencies in the enhanced VLA will allow studies of the very earliest phases of the radio emission after the supernova explosion.

Monitoring: early radio light curves

The radio emission from supernovae (SNe) is thought to arise at the shock between the outgoing ejecta and the progenitor star's circumstellar wind; the shock compresses magnetic fields and accelerates particles to relativistic speeds, giving synchrotron emission. This process is the same as in other synchrotron sources, but here we know where, when, and on what physical scale particle acceleration begins and proceeds, and can watch it occur over a large fraction of the life of the source. Further, as we can now model optical/UV spectra and photometry to derive the densities of both the ejecta and the circumstellar material (CSM), as well as the shock velocity, we can learn more about SN shocks than about any others outside the solar system. Unfortunately radio observations are somewhat complicated by the very CSM that provides the radio emission: this material is ionized by the initial optical/UV blast, and free-free absorption hides the intrinsic emission until days, weeks, months, or years after the explosion. This loses many of the interesting physical constraints on how fast the particles are accelerated, particularly at the highest energies. This changes dramatically if we can make sensitive observations at the high frequencies where the source first becomes optically thin (free-free absorption declines as $\nu^{-2.1}$). The enhanced VLA will make a dramatic impact on this field by probing directly the most interesting energy regime within days of the explosion. (SN 1994I was detected at 99 GHz within four days of optical discovery, and only logistical difficulties prevented it from being seen even earlier).

Aside from probing the effects of the young shock, early high-frequency detection would allow reliable determinations of the progenitor's mass loss and mass loss rate based on how much material is needed to mask the source at long wavelengths. This approach relies on knowing the inherent unabsorbed emission strength—currently a model-dependent extrapolation, not a direct observation. The derived CSM densities and density profiles are important first because they tie down models of SN optical/UV emission, and second because they tell us about the mass-loss history of the progenitor, a fundamental issue in stellar evolution. Finally, radio data taken during the first days after the explosion are the most useful, because they may be tied to simultaneous optical and UV data to develop and constrain detailed models of these sources.

Critical instrumental requirements are: frequencies of 40–50 GHz to access the highest-energy electrons and to minimize the effects of free-free absorption, rapid scheduling response (within days of optical detection) and high sensitivity (sub-mJy, phase coherent). The current 15–22 GHz system is ill-adapted to this work because of its low sensitivity.

Monitoring: broader frequency coverage

One gains enormously by measuring the frequency dependence of the emission over as wide a band as possible. The basic model parameters—CSM density, intrinsic spectral index and time dependence—are determined much more accurately by multi-frequency observations than by detailed observations at one wavelength. Also, the fundamental assumptions of most simple models—*e.g.*, that emission/absorption processes are scale-free—can be tested more directly. The main instrumental need is appropriate sensitivity in as many different bands as possible. This argues for the 40–50 GHz systems, as well as new 0.6 and 2.4 GHz receivers. Frequency coverage need not be continuous, but we need sensitive (few 10's of μJy in 5 min) systems for at least one high (40–50 GHz) and one low (0.6–2.4 GHz) band.

Monitoring: fainter sources

The biggest gain for detailed studies of individual objects is at high frequencies: a 2 GHz wide 40 GHz system could follow a 10mJy-peak supernova like SN 1994I for 40 days past maximum light with 5 minute scans, and obtain some data near maximum on sources as faint as 0.1 mJy. This would define the high-energy particle spectrum for normal Ib/c supernovae to a distance of 85 Mpc, and for the spectacular type II's a factor of 3 further out. The latter are particularly interesting, as none has yet been seen at mm wavelengths, although at least one (SN 1986J) emits copiously in the near-infrared.

Detection experiments become much more interesting with the enhanced VLA because sensitivity is increased comparably over a wide range of frequencies. For example, starburst galaxies are predicted to have about one supernova per year, yet directed searches have found no new radio supernovae. The current limits cannot rule out a population of less radio-luminous SNe (either intrinsic or heavily obscured by intervening free-free absorption). Both possibilities could be checked by deeper surveys at higher frequencies, where such absorption is minimized. H II galaxies, with star-formation rates of order a solar mass per year, should also make RSNe, and searches for those would also be aided by the increased sensitivity. It is important to realize that the supernovae we can study now at radio wavelengths are exceptional, with extremely high mass loss rates and strong shocks—lowering the detection threshold will let us detect more ordinary objects, and so learn about more typical stellar evolution.

SNe searches: going off the deep end

Much improved SN searches will be possible if there is at least one low frequency (1–2 GHz) where one can reach a noise level of a few μJy in 12 hrs over the entire primary beam. (Low frequencies are important because radio SNe decay more slowly at those frequencies.) For example, one might spend 12 hrs at λ20cm monitoring a distant starburst galaxy every six months or so in a wide configuration to minimize confusion. One should see radio SNe down to 20 μJy (7σ), corresponding to the detection of a type Ib/c to 220 Mpc ($z = 0.08$) or a strong type II (1986J) to 660 Mpc ($z = 0.21$, $\Omega = 1$). For a starburst galaxy at 100 Mpc, one should see even the dullest supernova, or a normal type Ib SN even fairly far down its light curve (within 200 days of the explosion), giving excellent limits on supernova rates in starbursts. At the same time one gets a good pencil-beam survey, and if the starburst is close on the sky to a relatively nearby galaxy, good limits on radio emission from type Ia SNe. The new correlator could be used for an H I survey at the same time. Another option would be to spend 12 hrs looking at a cluster: at 100 Mpc, the FWHM of the λ20cm primary beam is about 1 Mpc, so one could measure the radio SN rate in all the galaxies in the cluster at once.

4.2.2 Supernova Remnants

Some radio supernovae have been monitored for several decades after the explosion. They become SNRs some 100-1000 years later. We do not know what happens during the transition from RSN to SNR, *i.e.*, in the transition from interacting with the circumstellar material left over from the progenitor to interacting with the general interstellar medium.

The radio behavior during the SN phase diagnoses the history of mass loss from the progenitor, since the emission comes from the shock between the ejecta and the CSM. A sharp intensity decrease indicates the outer edge of the CSM, giving a timescale for the progenitor's slow wind, and yielding an estimate for the total mass loss for that star. This can be compared with stellar evolution and ISM enrichment theories, a comparison that is particularly interesting if the SN was observed optically. This has been done so far for only four SNe. The difficulty lies in tracking supernovae to very low flux levels; SN 1961V in NGC 1058 ($v_{\rm sys} = 518$ km s^{-1}) was recovered at about 0.2 mJy at λ20cm To reach a similar level in the Virgo cluster (about a factor of two further) we need 10 μJy rms noise, achievable in about 1 hr with the enhanced sensitivity; even with several pointings, the dozens of optically-known SNe in that cluster could be detected easily.

SNRs indicate recent massive star formation (stars that blew up $\sim 10^4$ years ago) and are the main source of the high energy particles (cosmic rays) that form the diffuse synchrotron emission in galactic disks and halos. They are important both in terms of energy input, disturbing the ISM, creating H I "bubbles" and possibly triggering further star formation, and as sources of metals in galactic disks. The current state of SNR detection is illustrated by recent observations of M33, where some 50 SNR were detected at an rms sensitivity of 50 μJy at 1.4 GHz. The cumulative distribution of SNRs as a function of flux density suggests either that incompleteness sets in at 0.5 mJy, or that the source counts may turn over there. Observations with a factor 10 higher sensitivity could be achieved in less than 2 hrs with the proposed 2.4 GHz system, and would settle this question beyond doubt. If the steeper power law is correct, this would yield a factor 20 more sources, or some 1000 SNRs. Confusion will be significant but one should be able to determine the supernova rate statistically with such large numbers. As well as obtaining a crucial parameter for models of energy input into the ISM, galactic abundances, etc. much more accurately, this would also give the "turnover time" for replenishing the cosmic rays in the galactic disk, which with more SNRs would be embarrassingly short. As well as such detailed studies, one could extend such observations to ~ 2.4 Mpc with 2-hr integrations, yielding more galaxies, and examining the dependence of SN rates and the available pool of particle accelerators on galaxy type and activity.

Resolving SNRs yields much more information than simple detections—it lets us distinguish SNRs from background sources by their morphology and also adds important physical information about the SNRs. For instance, the size gives an indication of the age of a remnant, and the relationship between size and surface brightness (the Σ-D relation) should also reflect the evolution of the source. The results of such studies in the Milky Way are muddled, at least in part, because of inhomogeneous samples and uncertainties in SNR distances. Studying SNRs in another galaxy provides better statistics (more SNRs, some indication of dependence on galactic environment, much better understanding of selection effects) *and* a common distance for all SNRs seen. Resolved images also give SNR types (filled, shell, or mixed), giving some indication of SNR histories and current power sources (pulsar *vs.* shock). Ideally one would like sub-parsec resolution at 0.6–2.4 GHz. The current A configuration would be useful for the larger sources, but the A+ configuration would be much better, giving a λ11cm resolution of ~ 0.3 pc at the distance of M33 (800 kpc).

These observations require high sensitivity over the entire primary beam at a low frequency. We need a high-sensitivity system at some frequency between 0.6 and 2.4 GHz; which frequency is not so important, nor does one need continuous coverage. Low frequencies are best because these sources have fairly steep spectra ($\nu^{-0.5}$ to ν^{-1}). One should also be able to image the entire primary beam at the highest available resolutions, to cover an entire galaxy or more with one pointing.

4.2.3 H II Regions

Extragalactic H II regions, direct tracers of luminous young stars, are traditionally studied in Hα, Hβ, and other lines characteristic of gas at 10^4 K. Radio observations, though difficult, offer two key advantages.

- The dust associated with star-forming clouds obscures the optical but not the radio emission, so radio flux densities better estimate the total star formation activity.
- High-frequency radio data reach much higher resolutions, so can disentangle complicated star forming regions.

The enhanced VLA would provide both the sensitivity and the resolution necessary for such studies.

A single O5 star creates an H II region with a flux density of about 1 mJy at 1 Mpc, or 10 μJy at 10 Mpc; a B0 star is 100 times less bright. The enhanced VLA at 40 GHz will reach a sensitivity of 2 μJy in 12 hrs with 1 GHz bandwidth; the super-wide 10 GHz bandwidth would make this much easier (1.3 hrs), but in any case we could count individual stars down to the B0 class in nearby galaxies. Even with the narrow 1 GHz band we could see a single O5 star at 10 Mpc in 12 hrs, and 10 GHz would allow either very fast imaging of distant sources, or a more involved but still plausible project to look at even smaller H II regions out to Virgo. One should pick up many more of the optically-detected H II regions, allowing the determination of extinctions, the direct measurement of temperatures and densities (useful for example in abundance work), and high-resolution imaging (see below). This might also be a good approach to finding possible star-forming regions in dwarf, elliptical, and low (optical) surface brightness galaxies, although direct Hα imaging probably wins when looking simply for detections.

Long-wavelength observations would be useful in distinguishing H II regions from faint background sources and SNRs, requiring a sensitive long-wavelength system (somewhere between 0.6 and 2.4 GHz). One would of course also get SNRs for free (see above), making this a wonderful star formation project.

The high angular resolution of the A+ configuration would be especially useful for this work. A typical H II region is a few to tens of parsecs across, and can be resolved in nearby galaxies even with the current VLA. Compact ($<$ 1pc) and ultra-compact ($<$ 0.1pc) H II regions, corresponding to much younger sources, are much more difficult to study outside our own galaxy. At λ9mm the A configuration gives $0.05''$ resolution, or 0.3 pc at 1 Mpc, and 3 pc at 10 Mpc; the extended A+ configuration is a factor 7 better, or 8 mas (0.04 pc at 1 Mpc, 0.4 pc at 10 Mpc, 0.55 pc at Virgo). Given the sensitivities discussed above, one could easily detect and image hundreds of individual ultra-compact H II regions in nearby galaxies, and even resolve compact H II regions to the distance of Virgo. This means knowing the ages and (high end) initial mass functions for star forming regions across entire galactic disks, in unprecedented detail, with no worries about extinction. This simply cannot be done now. (The MMA would do about as well, although in both cases, to eliminate confusing sources, the expanded VLA with high-sensitivity low-frequency systems would be needed.)

4.2.4 Extended Emission: Spectral Imaging

The radio emission from normal galaxies is dominated by synchrotron emission from relativistic cosmic ray electrons (CRE) and thermal free-free emission from ionized gas at $\sim 10^4$ K. The two processes are distinguishable mainly by their spectra: synchrotron emission is generally much brighter at low frequencies ($\sim \nu^{-0.5}$ to ν^{-2}), while thermal emission has a more slowly-varying spectrum ($\nu^{-0.1}$) at higher frequencies and may become opaque at low frequencies. Synchrotron emission therefore dominates up to about 20 GHz, while thermal emission is most important between ~ 30 and ~ 100 GHz. Disentangling the two in any individual galaxy requires sensitive imaging at the same resolution over as wide a range of frequencies as possible. As the separation depends on the behavior of the *total* flux density with frequency, it is essential to retain sensitivity to large-scale structures at all frequencies. This makes wide-field spectral imaging a particularly demanding problem in terms of sensitivity and u-v coverage. The enhanced VLA will be ideal for this work, combining high sensitivity and scaled-array capability across a huge frequency range with the ability to image a large range of spatial scales.

Synchrotron emission from galaxies is most readily studied at frequencies below a few GHz, since both the flux density and the size of the primary beam increase as one moves to lower and lower frequencies. As the loss rate varies as E^2, regions with little ongoing particle re-supply/acceleration have steeper spectra; the range from $\nu^{-0.5}$ to ν^{-3} has been observed in nearby galaxies. The sites and length scales of this spectral evolution, both in and out of the disk, tell us about where CRE are accelerated, and about the diffusion and convection processes that affect CRE within the disk.

The lowest frequencies sample the lowest-energy CRE which move farthest from their last acceleration point before their synchrotron emission is quenched. Radio "halos" of low-energy particles ($\sim \nu^{-2}$ to ν^{-3}) have been observed kiloparsecs above the disks of a number of edge-on galaxies at 1.4 GHz. In the few cases that have also been imaged at 327 MHz, even more extended structures have been found. The full extents and energy reservoirs of such cocoons of ancient particles around spiral galaxies are still unknown. The current 8-antenna system at 74 MHz has neither the sensitivity nor the spatial sampling to image (faint) galaxy halos properly; here we make a special plea for outfitting all 27 VLA antennas with 74 MHz receivers, to study such steep-spectrum sources. With an expected sensitivity of 5–10 mJy in 12 hrs, one could image NGC 891 at 74 MHz with $20''$ ($0.7h^{-1}$ kpc) resolution. Such an image would be as sensitive as any current higher-frequency one, given only the electrons we already know about from 1.4 GHz images; since we expect a much older population as well, the 74 MHz images should show more emission, even further from the disk. With the A+ configuration one could achieve $7''$ ($0.26h^{-1}$ kpc) resolution, offering an unprecedented view of both the disk-halo interface and of any structure in the halo itself. By probing the oldest and most extended cosmic ray populations, 74 MHz data offer the unique prospect of measuring the total time over which cosmic rays have been produced, as well as the extent of the galaxy's magnetic field. We also need the higher resolution available around 1 GHz to study the the detailed changes in spectra with height above the disk and so to place direct constraints on models for cosmic ray diffusion/convection, as well as theories about the origin of chimneys, bubbles, and other phenomena connecting disk to halo. With the enhanced sensitivity, one could match individual SNRs and HII regions to individual outflows above the disk, and track the aging of the electrons as they escape from the plane.

At 0.3–2.4 GHz, we can study the spectral aging of particles within and somewhat above the disk. The big gains of the enhanced VLA are (1) higher sensitivity, allowing observations of more normal galaxies at higher resolution; and (2) better frequency coverage, allowing more detailed imaging of subtler spectral changes.

The thermal component dominates the synchrotron emission from normal galaxies at 30–40 GHz. This regime is currently unexplored, because no imaging instrument has simultaneously the high sensitivity, high resolution, and large field-of-view to make this work practical. The VLA Development Plan addresses all these difficulties. The particular aspects of interest are

- as wide a bandwidth as possible for some band between 40 and 50 GHz, for maximum sensitivity;
- the E configuration, for maximum surface brightness sensitivity and resolution matched to the longer wavelengths in A or B configuration (the beam at λ9mm in E configuration would be about $6''$, roughly like that of the B configuration at λ20cm);

- simultaneous total power measurements if at all possible, to fill in the missing short spacings;
- good snapshot capability, to allow mosaicing of many pointings (λ9mm gives a $1.4'$ field of view).

The diffuse ionized gas with emission measures of a few might be detectable with long integrations and 10 GHz bandwidths: a $6''$ beam filled with the warm ionized medium as seen in the Milky Way would give a flux density of 0.2 μJy/beam at λ8mm. (This would incidentally give the best possible limits on diffuse ionized gas in ellipticals, since the deepest optical techniques rely on having fairly narrow and well-known velocities.) More reasonable integrations could trace faint star-forming complexes or regions of high electron density for the first time at radio wavelengths. Knowledge of the true thermal emission is also critical to disentangling the thermal and non-thermal emission, as discussed in the next section.

The primary difficulty in disentangling synchrotron emission with varying spectral index from thermal emission is the limited spectral range now available. The discussion above focussed on improvements at a few frequencies, but the real strength of the enhanced VLA comes when all those frequencies are combined. With so many measurements of the radio spectrum available as a function of position in a galaxy, one can finally hope to image the thermal and non-thermal emission *separately*, following the spectral aging of the synchrotron component with good spectral index sensitivity over a wide range of spatial scales. The combination of high- and low-resolution observations will allow both the identification of SNRs and HII regions, and their removal from the low-resolution images needed to trace more diffuse structures. This is essential to any detailed understanding of galaxies in general and the interstellar medium in particular. To take a single example: one of the great puzzles found by the Infrared Astronomical Satellite (IRAS) was the FIR-radio correlation, which shows an incredibly tight relation between FIR and radio emission over many orders of magnitude. The origin of this relationship, and the heat sources for the dust which emits the FIR radiation, remains controversial. While the dust must be heated by stars, whether those stars are mostly the very bright ones in HII regions, or the more diffuse population of A and B stars, is still debated. On the radio end, the synchrotron emission can presumably be traced eventually to SNRs, but the details of this are not at all clear. The Infrared Space Observatory (ISO) and such ground-based instruments as SCUBA on JCMT will provide high-resolution probes of the FIR emission; the enhanced VLA will make similarly-detailed images available at radio wavelengths, and more importantly, show whether the FIR-radio correlation is tighter when done with pure thermal/non- thermal emission (either or both might be expected...). Assuming we do understand this correlation, various authors (esp. Helou) have used the details of the relative FIR/radio distribution to constrain cosmic ray diffusion lengths; these models can only be tested and refined through high-resolution, multi-wavelength studies.

4.2.5 Polarization

The sensitivity of the enhanced VLA, combined with the good frequency coverage provided by the proposed receivers (particularly the 2.4 GHz band), makes it possible to make polarization measurements of much fainter and more diffuse sources. The experiments described below all require good sensitivity and good resolution at the low frequencies, and polarization capabilities at least as good as the current systems (1%) at noise levels of a few μJy. We also need to achieve dynamic ranges of $\sim 10^5$:1 routinely.

Polarization of SNR/SNe

No polarization has ever been detected in an external SNR/RSN. Since galactic remnants are highly polarized but often symmetric, this is presumably a combination of poor resolution and insufficient sensitivity. The enhanced VLA would solve both problems: the extended A+ configuration provides $0.08''$ images at 2.4 GHz, corresponding to sub-parsec resolution out to 2.6 Mpc, at sensitivities of 50 μJy in 2 hrs. This is sufficient to image 1% polarization in remnants as strong as Cas A out to that distance. For RSNe, resolution is obviously impossible, but much more rigorous limits could be placed on the integrated polarization, and consequently on the symmetry of the supernova.

Radio halos

Only a few radio halos have been reliably imaged in polarization, those of NGC 4631 and NGC 891 being the best examples; the strong and well-ordered magnetic fields inferred far above the disks of these galaxies are intriguing, but may indicate the peculiarities of those systems rather than any general trend. Knowledge of magnetic field structures at high-z is important both for understanding diffusion of cosmic rays above the disk, and for arguments about the relative strength of the pressure/energy in magnetic fields, cosmic rays, and thermal particles. With the enhanced VLA, one could go a factor 10 deeper than the best current 1.4 GHz images of NGC 891, and start looking at normal rather than actively star-forming galaxies.

Galaxy disks

The evolution of large-scale magnetic fields in galaxies is at best poorly understood, with simple models (*e.g.*, axisymmetric/bisymmetric fields) that observations already show to be woefully inadequate. With the theorists frustrated, the hope is that more numerous and more detailed observations will make the physics of what's going on a bit clearer. The enhanced VLA will be able to investigate magnetic fields down to much smaller scales, and in a much larger sample of galaxies than the ~ 15 already imaged. A 1-kpc beam at Virgo (15 Mpc) would be about $15''$, and would (for a typical disk) give a flux density (I) of 300 μJy/beam. Assuming a polarization of 10%, one requires a noise level of 4.3 μJy/beam to see this at 7σ, an experiment which would currently require 24 hrs, but which could be done in under 3 hrs with the enhancement. More local galaxies could be imaged at much higher resolution, showing the magnetic field structure down to 75 pc (at 1 Mpc) in a similar time.

4.2.6 Imaging Starburst Galaxies

Regions of intense starburst activity within 1 to 2 kpc of the nucleus contain the clues to a host of fundamental questions about the Universe. Among these are: The unclarified physical processes involved in the formation of stars—in this case especially stars of high mass—the detailed mechanisms which cause a starburst phase to be self-limiting (*i.e.*, it snuffs itself out by removing its interstellar gas), how the supernova-generated cosmic rays are diffused; how the hot star + supernova-generated energy is dissipated into the dense ambient gas, the latter's chemical and thermal properties down to sub-parsec scales; how the collective starburst winds are able to amplify (and seed?) the strong, organized magnetic fields which are found in the outflow material; and the mechanism of the *organized* expulsion of thermal gas, dust, and cosmic rays into the halo and the surrounding IGM.

Starbursts are connected in as yet unknown ways to a wider family of galaxy systems which include active galactic nuclei, radio quiet QSO's, Seyfert galaxies and quasars, all of which release large amounts of energy at or near a galaxy nucleus. Starbursts, which the enhanced VLA could study in minute detail in the nearby universe, were most certainly very prevalent in the earliest galaxy generations. Thus a thorough understanding of "local" starbursts, such as M82, are needed to reconstruct the physical scenario which explains the formation of the first galaxies, hence the cosmic evolution of galaxies. The early-universe starburst scenario includes the rate of production of heavy elements, and the outflow-seeding of the IGM with metal-enriched gas, cosmic rays, probably accompanied by magnetic fields.

Images of starburst nuclei such as M82 reveal the complexity of both the inner starburst engine and the outflow process at a maximum resolution of a few parsecs. The emission contains a complex, though not yet fully resolved mix of thermal and non-thermal radio emission, with striking variations of spectral index on many angular scales.

The proposed improvement in the VLA's resolution (7-fold), sensitivity ($\geq 20\times$), and spectroscopic capability will enable great progress in unraveling the "unknowns" listed above. Because optical, UV and X-ray extinction make this important class of system accessible only in the radio and infrared, the enhanced VLA will be *required* in these investigations. No forseeable infrared device will be capable of these angular resolutions.

4.2.7 Instrumental Requirements

The recurring theme in this working group was high sensitivity at high frequencies over a wide range of angular scales. We need the quoted sensitivity, for at least 1 to 2 GHz bandwidths (and preferably for a 10 GHz band!), between 15 and 50 GHz; and we want this for *weak* (10-μJy) sources, even in the A+ configuration. We *must* be able to phase-reference at this level, we *must* have good surface accuracy and pointing, and we *must* be able to handle the consequent high data rates. E configuration is also very helpful, for surface brightness sensitivity at these high frequencies. Continuous frequency coverage is not necessary, but wide bandwidths are.

The most sensitive possible system at 1 to 2 GHz is also needed for spectral imaging, both of diffuse and of unresolved sources, whether this system is at 1.4 or 2.4 GHz. We need the highest possible sensitivity, perhaps through wide bandwidths with (on-line?) RFI excision; this also implies high dynamic range. 74 MHz receivers on all VLA antennas would be specially useful for studies of radio halos and the of most extended outskirts of galaxy disks. Continuous frequency coverage is not necessary but we must be able to image the entire primary beam.

We need polarimetry of weak sources with 1–2 GHz bandwidths, to the same accuracy we achieve now ($\sim 1\%$). Again, we would like to image the entire primary beam.

To take full advantage of the upgrade, we would like the correlator to permit imaging the whole primary beam in the A configuration or beyond between λ1.3cm and λ90cm, without bandwidth or time-delay smearing. For the A+ configuration, this means about 2000 channels, 0.3 sec averaging times, and 33 antennas, for a (sustained!) rate of about 1.6×10^7 visibilities per second (full polarization mode). This might be halved by using longer averaging times and fewer channels on the short baselines, but not much further than that. Without the A+ configuration, the numbers are more reasonable— 400 channels, 1 second averages, and 27 antennas, for a sustainable rate of 6×10^5 visibilities per second (full polarization).

The E configuration is needed mainly to image diffuse low-level emission at high frequencies. Snapshots are less important than long, sensitive observations. Total power measurements from *somewhere* must be available to allow imaging at high frequencies; mosaicing must also work.

Frequency agility is essential for the study of time-variable sources, where simultaneous high-frequency (≥ 20 GHz) and lower-frequency observations would be very powerful.

Overall, there are three top-priority items, in the order (1) new correlator, (2) μJy sensitivities at some high frequency (> 20 GHz), (3) μJy sensitivities at some low frequency (1–2 GHz, depending on RFI). The new configurations are interesting but not as crucial. Whether the E configuration or the A+ configuration is more important depends on the kind of science one is interested in.

4.3 SPECTROSCOPY OF NORMAL GALAXIES

4.3.1 Neutral Hydrogen in Individual Galaxies

The new 1.4 GHz receivers already provide impressively low system temperatures, so an important part of the 1.4 GHz upgrade has already been accomplished. The new correlator and the E configuration will also allow progress in studying H I emission from normal galaxies. To allow imaging of an entire, rapidly rotating, large spiral the correlator should cover a velocity range of at least 1000 km $s^{-1}$to allow for good continuum subtraction. Channel sizes should be adjustable by factors of two, with a channel of approximately 2.5 km s^{-1} and 1.25 km s^{-1} available to resolve the smallest anticipated width of the H I line (currently in the range 5 to 10 km s^{-1}) in most systems. The new correlator would allow detailed studies of the ISM in galaxies out to the distance of Virgo and spiral structure studies somewhat farther. The variety of environments observable out to Virgo should exhibit a wide variety in ISM structure, including the possibility of testing proposals that H I is formed primarily from dissociation of molecular hydrogen. The E configuration will allow more sensitive searches for faint outer parts of galaxies to determine where spiral disks end, for bridges between neighbors to set limits on interaction in normal systems (*e.g.*, the Milky Way and M31), and for extended streamers in interacting systems.

4.3.2 Neutral Hydrogen Surveys

The enhanced VLA will have a major impact in the area of *unbiased surveys* in the neutral hydrogen line. For continuum observations the VLA has been unsurpassed as a surveying instrument, with a collecting area that is only second to Arecibo, combined with the large field of view. For blind H I surveys a third dimension comes into play—the instantaneous redshift range that can be covered. The new correlator will be more powerful in that respect than any currently operational or planned correlator on a synthesis instrument. Thus the VLA will become the most powerful H I surveying machine by far. Extending the 1.4 GHz band down to ≈800 MHz would allow the direct study of galaxy evolution by imaging the H I emission of galaxies in $0 < z < 0.8$. While the highest redshift at which H I has yet been detected in emission is about 0.08, the enhanced VLA could detect thousands of galaxies at redshifts from 0.2 to 0.8 in a 100-hr integration.

The large scale structure of the universe as we know it today, with its large filaments, sheets, walls and voids, is based almost entirely on observations of high-luminosity galaxies, observed at optical wavelengths. Biased galaxy formation predicts a separation between luminosity (bright galaxies) and mass (dark matter). Dwarf galaxies are expected to be more uniformly distributed. Since nearly all investigations of the properties and spatial distribution of galaxies begin with optically (or IRAS) selected galaxy catalogs, any population of gas clouds with very low optical luminosity or surface brightness could have largely escaped detection. Direct searches in the H I line circumvent these optical selection biases.

Examples of questions to be addressed by such surveys are the abundance of gas rich dwarfs and the study of their spatial distribution. Do they follow the optically bright galaxies or are they distributed more uniformly as predicted in some theories of galaxy formation. It will become possible to construct an unbiased H I mass function for the first time. A complete inventory can be made of the H I content in the local universe, the size and mass distribution of H I disks. Galaxies may be found in the zone of avoidance and new light may be shed on the parent population of nearby Ly α absorbers. At larger redshifts, the structure of clusters of galaxies and voids may may be determined. At even higher redshifts entirely new ground will be trodden. The H I properties of galaxies at $z > 0.1$ will be studied for the first time, and it will be possible to study the upper end of the H I mass function out to $z \approx 1$. This might settle once and for all whether the gas reservoirs around galaxies increase with increasing redshift, and whether entirely new gaseous galaxy types occur at these higher redshifts.

Below we present three examples of such surveys, one concerning the local universe and employing the extreme surface brightness sensitivity of the E configuration, one performing simultaneously an in-depth study of a cluster at a redshift of 0.1, combined with a deep pencil beam survey covering a range from $0 < z < 0.2$ to be done with the C configuration. The third survey is aimed at studying the evolution of the gas reservoirs around galaxies in the range from $0.2 < z < 0.8$ with the resolution of the B configuration.

An all-sky H I survey in $0 < z < 0.1$

In recent years all sky continuum surveys covering almost the entire electromagnetic spectrum have become available, giving us a good indication of the stellar, dust, hot gas and relativistic electrons distribution in the universe. However for the most abundant element, neutral hydrogen, this information is lacking. In fact, we don't even know the H I content of the local group of galaxies.

The high surface brightness sensitivity of the VLA E configuration, combined with the large instantaneous velocity coverage of the correlator will finally make it feasible to survey H I over the whole sky, simultaneously covering a redshift from 0 to 0.1. This will give a *complete inventory of H I masses irrespective of a stellar association* to $10^5\ M_\odot$ within the local group, to $2.6 \times 10^7\ M_\odot$ at the distance of Virgo Cluster, $2.4 \times 10^8\ M_\odot$ in Coma, to $3.5 \times 10^{10}\ M_\odot$ at the survey limit at a distance of $280\mathrm{h}^{-1}$Mpc. Note that even in the nearest cluster, Virgo, only a few percent of the total volume has yet been searched for HI. The total search volume of this survey, $6.5 \times 10^7\mathrm{h}^{-3}\mathrm{Mpc}^3$, is such that about 10^6 galaxies should be detected with H I mass less than $10^{10}\ M_\odot$.

The assumed survey parameters are an integration time of 3 minutes per pointing, giving a column density sensitivity of 3×10^{18} cm^{-2} over a $2.5'$ beam, using a total bandwidth of 125 MHz and 2048 channels of 12.6 km s^{-1}. The entire sky north of $-30°$ can then be observed to the 6σ mass limits noted above in a (mere) 2.7 yrs.

The structure of a cluster of galaxies, combined with a pencil beam survey

At higher redshifts, an entire cluster fits into one primary beam. For example at $z = 0.1$, an Abell diameter is about $20'$, so we can study an entire cluster in one pointing, giving the spatial and kinematic distribution of all the gas-rich objects in and around it. The resolution of the C configuration provides some spatial information for individual galaxies. A 36-hr integration would (at $z = 0.1$), allow a 6σ detection of $7 \times 10^8\ M_\odot$ of H I with 100 km s^{-1} line width. A total band of 62.5 MHz is needed, corresponding to 13,000 km s^{-1} split up in 2048 channels of 6.3 km s^{-1}. The spatial and velocity distribution of the gas-rich galaxies will provide information on the dynamical state of the cluster, whether it is relaxed or still collapsing. The velocity coverage of 13,000 km s^{-1} is twice that needed to cover a typical rich cluster, so many foreground and background spirals will also be detected.. The 6 km s^{-1} accuracy of the velocity profiles will make it possible to derive useful Tully-Fisher distances to the galaxies and thus to probe deviations from the Hubble flow out to many Mpc from the cluster. These observations will also provide a useful data base to compare with cluster studies at higher redshifts aimed at determining the evolution of the gas content in clusters.

In parallel with such deep integrations a sensitive pencil beam survey can be carried out to sample the entire conical volume within the primary beam between $z = 0 - 0.2$, using 250 MHz bandwidth and 1024 channels of 250 kHz (50 km s^{-1}). H I masses of $4 \times 10^9\ M_\odot$ will be detectable at the survey limit of $z = 0.2$, implying that normal galaxies with modest H I content can easily be detected. Note that currently the highest redshift at which H I in galaxies has been detected in emission is about 0.1. Within each search volume of $5 \times 10^3 \mathrm{h}^{-3}\mathrm{Mpc}^3$ we expect to detect a few hundred galaxies with H I mass less than $10^{10}\ M_\odot$.

The evolution of gas content at $0.2 < z < 0.8$

Recent Hubble Space Telescope results indicate that both field and cluster galaxies are undergoing dramatic evolution at $z \sim 0.5$. A relative increase in the number of spiral-like galaxies is found, representing interacting and merging galaxies in clusters and a population of blue field galaxies unlike anything seen in the local universe. A major question is how does the gas content of galaxies evolve at these redshifts, it is expected to increase with redshift. Extending the frequency coverage to 800–1200 MHz would allow us to probe this critical phase in galaxy evolution in the redshifted H I line. Making the conservative assumption that H I line fluxes at $z = 0.5$ are similar to the largest seen in the nearby universe, namely $3 \times 10^{10}\ M_\odot$ with a velocity width of 300 km s^{-1}, a 6σ detection can be made in 100 hrs at that redshift. The largest possible bandwidth should be used to probe the entire redshift interval from $z = 0.2$ to 0.8 simultaneously, if the correlator capacity would permit (500 MHz and 2048 channels). Each field observed would then sample a total volume of $3.2 \times 10^5 \mathrm{h}^{-3}\mathrm{Mpc}^3$, subject to limitations imposed by RFI. An unknown number of H I luminous objects might be detected in the interval $0.5 < z < 0.8$, but more importantly, assuming only local space densities and H I luminosities we can expect detection of more than 10^3 galaxies per field in the interval $z = 0.2$ to 0.5, revolutionizing our understanding of galaxy evolution. Such a survey would be done in the B configuration, matching the beam size to the typical galaxy size at those redshifts.

4.3.3 Instrumental Requirements for Neutral Hydrogen Surveys

The all-sky survey would benefit tremendously from every possible improvement that can be made to the E configuration sensitivity. For example construction of a ground screen and interference fence under and around this compact configuration could redirect a significant fraction of the far side lobe power onto the cold sky. Cooling of the polarizer assembly should also receive a high priority to improve system performance. High dynamic range receivers must be employed to minimize data loss due to saturation by RFI. Low loss, preferably tunable, RF filters will probably also be necessary to allow operation in the hostile RFI environment. Minimizing data loss by shadowing and cross talk in the tightly packed E configuration might also dictate an elliptical configuration with a NS to EW aspect ratio of about 1.5:1.

The surveying speed is directly proportional to the instantaneous velocity coverage that can be used, this drives the request for implementing the possibility to use 500 MHz and 2048 channels. Since interference will be a major problem at the lower frequencies, schemes of online rejection of interference need be investigated.

Comparison with existing and planned instruments

As pointed out earlier, the three parameters that determine the surveying speed are field of view, sensitivity and instantaneous bandwidth. The GMRT has a larger collecting area than the VLA and will be more sensitive at the lower frequencies. The currently planned correlator will allow for an instantaneous bandwidth of 32 MHz at most. Thus the enhanced VLA will be a factor of ten faster. Note also that the GMRT has no plans to install feeds for the frequency range between 760 and 1000 MHz ($0.4 < z < 1$), currently thought to be one of the most interesting regimes for galaxy evolution. The WSRT will cover this frequency range but its collecting area is half of the VLA's and (more importantly) to get sufficient spectral resolution (66 km s^{-1}) one can at most use a bandwidth of 80 MHz, so the VLA will be 5 times faster. Arecibo gains by a factor five in collecting area, so will play a major rôle in directed studies of *known* high-z objects. As a surveying instrument however, it loses by a large factor (about 25) relative to the VLA, because of its much smaller field of view. Synthesis arrays are also much less sensitive to interference, a major restriction on work at those redshifts.

4.3.4 Radio Recombination Lines from Extragalactic Sources

The theory of extragalactic radio recombination lines (RRLs) has predicted for almost 20 years that we should be able to detect RRLs from galaxies and QSOs. The lines are expected to probe physical conditions in ionized gas around the nuclei of starburst galaxies and AGN's. The first detection of RRLs from two galaxies beyond the Magellanic Clouds (M82 and NGC 253) were made in 1977. Despite many efforts no further detections were made until 1991, when a line was detected from NGC 2146 at mm wavelengths. In 1993, Anantharamaiah *et al.* detected RRLs at λ3.5cm from 9 of 14 starburst galaxies using the VLA and the ATCA, and successfully imaged the velocity field within several hundred parsecs of the centers of these starburst galaxies (see Fig. 4.1).

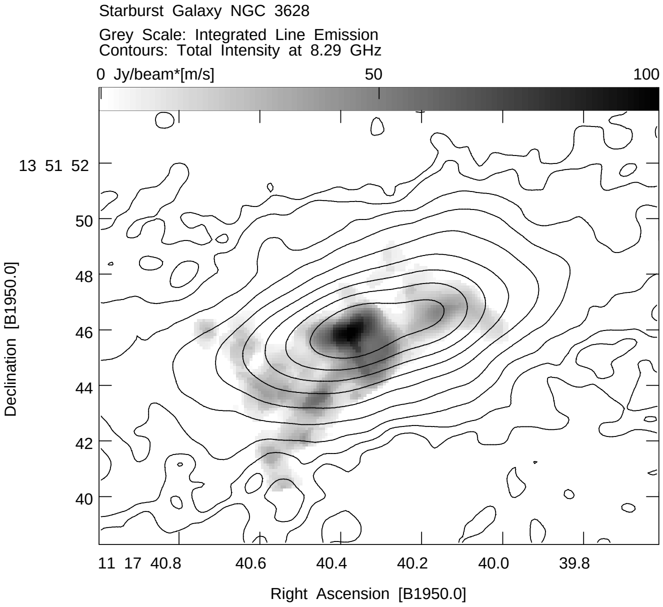
These detections open a new field of research. The strong radio continuum radiation from radio galaxies and quasars will make it possible to detect stimulated recombination line emission out to a large redshift, providing a unique tool for exploring the dynamics of the central regions of AGN's. Starburst galaxies will be detectable to several hundred Mpc.

The detected lines have widths of 300 to 700 km s^{-1} and line to continuum ratios of 1% to 0.1%. Clearly the past failures to detect these lines were mainly due to poor spectral dynamic range. The enhanced VLA will be especially suited to this work. The required spectral dynamic of 10^5 to 1 should be achievable with the replacement of the wave guide by optical fibers. The possibility to cover a total bandwidth of 1 GHz (two IFs) is especially interesting, since many different transitions fall within 1 GHz. For example, at 2.76 GHz, 20 different transitions can be observed within 1 GHz and as many as 50 at 1.42 GHz. These bands are especially suitable for searches for stimulated emission. To improve sensitivity a combined profile could be made of all the transitions, or alternatively, if line intensity ratios can be obtained from adjacent transitions, it will become possible to differentiate between stimulated and spontaneous emission.

4.3.5 OH Masers in Nearby Galaxies: the Birth of O and B Stars

In the Milky Way, the prominent emission of OH at the main line frequencies 1665 and 1667 MHz is associated with star–forming and H II regions. These galactic type I OH masers generally exhibit velocity widths of 1 km s^{-1} or less, and the radiation is strongly (in some cases 100%) polarized. Studies of various associated constituents observed at optical, IR and radio wavelengths indicate a picture in which the OH maser arises in a dust envelope just outside the Stromgren sphere of gas in a compact H II region. As the ionization front expands through the maser, the OH molecules are dissociated so that the maser eventually disappears. The dynamic lifetime of such masers is only about 10^3 to 10^4 years; OH masers therefore may represent a fleeting phenomenon associated with the birth of one or more O–B stars. By studying the main line OH emission seen in nearby galaxies, we may measure the current rate of star formation of such stars in those systems. This determination can be compared with those derived from other indicators, such as thermal radio continuum emission or optical/IR emission from H II regions. Likewise, since the size and luminosity of H II regions is a promising distance indicator, it is critical to understand more fulling the occurrence and physical conditions of star–forming regions in nearby galaxies.

The peak luminosities seen in most extragalactic OH sources are much greater than those of typical galactic type I masers. In the megamasers such as NGC 253, M82 and IC 4553 (Arp 220), peak luminosities exceed 10^6 Jy kpc^2. The strongest OH type I maser, W49N, shows a peak luminosity of only about 3×10^4 Jy kpc^2, and typical strong galactic sources are about a



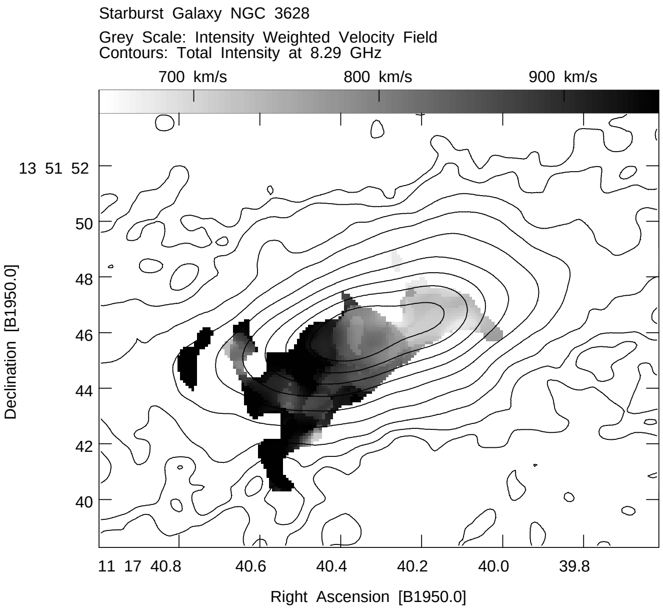


Figure 4.1: H92α images of the nuclear region in NGC 3628 made from the VLA observations by combining C and B configuration data; the angular resolution is $1.8'' \times 1.5''$. *(upper)* integrated H92α line emission (grey scale) and continuum emission at λ3.5cm (contours). *(lower)* the intensity-weighted velocity field (grey scale) and continuum emission at λ3.5cm (contours).

factor of ten fainter. Individual maser sources have been detected in the Magellanic Clouds and M33. The difficulty in detecting OH emission from Type I masers in other galaxies arises from the combined requirements of adequate sensitivity ($<$ 1 mJy rms), high resolution ($<$ 5 kHz), broad total bandwidth ($\sim$ 5 MHz) and both polarizations. Surveys for stellar OH masers would be practical out to 10 Mpc. As these masers occur in the early phases of evolution of massive stars, they might be used to probe, not hampered by extinction, the formation of very massive stars.

4.3.6 Water MegaMasers: Nuclear Dynamics in Nearby Galaxies

Megamasers (the H_2O maser at λ1.35cm) are very strong, of the order of 2000 Jy at 1 Mpc. They are uncommon: near the centers of starburst galaxies. The line-widths can be very large: (NGC4258) up to 1000 km s^{-1} rotation has been found on a length scale of 0.1 pc ($\rightarrow 2 \times 10^7$ $M_\odot$). The enhanced VLA could be used to survey the megamasers in known starburst IRAS bright galaxies. The enhanced VLA (sensitivity $\sim$ 0.15 mJy/10min/100 km s^{-1}) and larger bandwidth 2000 km s^{-1} (156 MHz)—about 20 times faster than current VLA) could detect such megamasers out to $\approx$316 Mpc at the 10σ level. A large number of such systems could thus be identified.

Followup with the VLBA would be a promising way to identify extragalactic black hole candidates independently of their nuclear radio continuum. The VLBA could yield proper motions of many masers in the host galaxies, and/or the direction of rotation of these systems. The combination of the expanded VLA and the VLBA could therefore be a powerful tool for exploring the dynamics of galactic nuclei independently of their continuum radio luminosities, and thus for an unbiased study of the relationships, if any, between these dynamics and the formation of an AGN.

4.3.7 Molecules in Nearby Galaxies

Interferometric studies of CO have so far been limited to the lower transitions of the molecule, tracing low-density gas. Other molecules are better tracers of molecular gas temperature and density, and many have been observed in external galaxies using single dishes. Some of these molecules (CS, HC_3N, H_2CO) have been observed at the higher transitions due to the limited range of frequencies attainable by the millimeter telescopes; often if the lower transitions have been observed, it was with low-sensitivity systems incapable of making detections in external galaxies. In the enhanced VLA, several observing bands (in particular the 22.5, 33, and 45 GHz bands) will be sensitive enough to image several of the lower transitions of many molecules in external galaxies. This will allow us to determine the variations in physical conditions across galaxy disks.

CS(1$\rightarrow$0) occurs at a frequency of 49 GHz, placing it in Q Band; unfortunately other transitions fall outside the range of the VLA receivers. The line is fairly strong; it should be useful in probing molecular cloud dynamics. Besides Galactic detections, CS has also been detected in external galaxies. For NGC6946 and Maffei 2, peak main beam temperatures were $\sim$ 0.03K for the CS(3$\rightarrow$2) transition in the nucleus; if the source is resolved, it would take about 13 hrs with the enhanced VLA to make a 2σ detection (assuming the same peak temperature at the CS(1$\rightarrow$0) transition) in the D configuration. E configuration observations would of course go much faster and still have resolution on the order of 5$''$; this configuration could be used to mosaic larger regions of the galaxy disks. Brighter CS(2$\rightarrow$1) peak temperatures have been found throughout M82, so integration times would be shorter for this galaxy.

Cyanoacetylene (HC_3N) is a molecule which gives information on density distribution. Several transitions appear in the observing bands of the VLA ranging from the J=1$\rightarrow$0 transition at 9 GHz to the J=5$\rightarrow$4 transition at 45 GHz. Higher transitions of HC_3N have been observed in external galaxies; a component in the nearby spiral NGC253 emits its strongest radiation near the J=5$\rightarrow$4 line, which falls at 45 GHz. The peak main beam temperatures is $\sim$ 0.085K for the HC_3N J=9$\rightarrow$8 transition in the nucleus; if the source is fully resolved, it would take about 6 hrs with the enhanced

VLA to make a 3σ detection in $HC_3N(5\rightarrow4)$ the D configuration. For similar peak temperatures in the upgraded 22.5 GHz band, a 3σ detection in HCN($2\rightarrow1$) would take 9 hrs.

Other molecules with transitions falling in the enhanced VLA band include formaldehyde (H_2CO), methyl acetylene (CH_3C_2H), and methyl cyanide (CH_3CN), each an excellent tracer of density and/or temperature with at least three transitions falling in the 15. 22.5, 33, and 45 GHz bands. Sulfur monoxide (SO), which traces oxygen-rich regions of clouds, also has several transitions which fall in the enhanced VLA band.

These observations would not be possible without the sensitivity proposed for the higher frequency bands in the VLA Development Plan. Also, at these frequencies we need large bandwidths to cover the velocity range typically found in external galaxies (hundreds of km s^{-1}); the larger channel widths of the new correlator are required to ensure proper coverage. If flexibility is built into the correlator, two or more of these lines can be observed simultaneously, allowing quick determination of physical parameters across the galactic disk. The E configuration will be needed to mosaic larger objects (since the primary beam at 45 GHz is $1'$).

4.4 ACTIVE GALACTIC NUCLEI

4.4.1 The State of Radio-galaxy Physics

The most plausible mechanisms for energizing large, powerful extragalactic sources from AGNs involve well-collimated outflows near the symmetry axes of accretion disks around black holes. The black-hole potential well is needed (a) to generate the observed luminosity at high efficiency and (b) to provide the relativistic outflow velocities implied by super-luminal proper motions on parsec scales. The importance of well-focused outflows on large scales in these sources was only a promising theoretical idea (motivated by a few hints of jet-like structures in 3C sources) until VLA data showed that:

- radio jets are indeed ubiquitous in radio-loud AGNs;
- key *global* properties of the jets (their brightness asymmetries, their prominence relative to other extended structure, and some systematics of their polarimetry) correlate (a) with the total radio power of the AGN and (b) with whether it is a radio galaxy or a quasar;
- feature velocities near or above c are present on *kilo*parsec scales in M87, which contains one of the nearest highly-asymmetric radio jets;
- where jets are found on both parsec and kiloparsec scales in the same object, the brighter large-scale jet is always a plausible continuation of the brighter parsec-scale jet;
- in sources with prominent one-sided jets (which are more likely to be oriented near the line of sight on this hypothesis), the depolarization asymmetries of the radio lobes correlate with the jet brightness asymmetry, as if the brighter jets are indeed on the side of the source closer to the observer.

These results encourage models that "unify" the known populations of compact and extended radio-loud AGNs assuming relativistic outflows, a range of orientations relative to the line of sight, and an obscuring torus whose geometry controls how close to the AGN we can probe with optical spectroscopy. It is now widely accepted that most, if not all, radio-loud AGNs are energized by jets that are *initially* relativistic.

It is much less clear whether, and under what conditions, outflows from AGN *remain* relativistic as they propagate away from the AGN and interact with the ISM, the IGM and/or their own ejecta.

The enhanced VLA will allow an attack on this problem, as described below. The extent to which relativistic Doppler favoritism and aberration dominate the appearance of large (kpc-scale and greater) radio features in sources of different radio powers is also unclear. There is evidence that large-scale sources have some asymmetries that are relativistic illusions and others (size, spectral asymmetries) that are intrinsic. To understand the dynamics and the evolution of large-scale radio sources in real circumgalactic environments, we must determine how jets interact with their surroundings in sources with a wide range of powers and in a wide range of environments.

4.4.2 Jets

To make progress in this area, we now need to explore the *internal structures* of radio jets rather than their global properties. As we describe below, combinations of analytic and numerical models of relativistic jets can predict internal structural aspects of the jets that will be accessible to the enhanced VLA but which can only be glimpsed in a few special (bright, nearby) cases with the present instrument.

Low power sources: jet deceleration?

In low-power radio galaxies without hot spots (Fanaroff-Riley Class I structures—FR I), the jets usually symmetrize on scales of a few kiloparsecs or less, suggesting that bulk relativistic motion in these jets is confined to the basal regions. It is becoming clear, however, that the basal regions that can be resolved with the VLA share the brightness asymmetries of the first few parsecs that can be imaged by VLBI, *i.e.*, that an asymmetry which begins on parsec scales persists to kiloparsec scales. It is therefore important to establish if, and if so how and where, such flows decelerate between the parsec and kiloparsec scales. The jet dynamics are thought to be dominated by turbulent entrainment of material from the galactic atmosphere in a boundary layer that (a) decelerates and (b) spreads to fill the jet volume. Models have been developed that predict explicit relationships between the internal brightness and polarization structures of the jets including the effects of such boundary layers. Variations in flow velocity both across and along the jets strongly affect Doppler favoritism and relativistic aberration (which can determine the perceived polarization state). The models can therefore predict relationships between brightness asymmetries, limb-brightening and apparent polarization states across and along the jets and their counterjets, if the jets are intrinsically similar on both sides of the AGN (as suggested directly by their large-scale properties). Specifically, if counterjet emission can be detected in the "gaps" close to the AGN in current VLA images, it should be found to have longitudinal magnetic fields with a higher degree of linear polarization than the main jet at similar distances. The counterjet emission should be limb-brightened nearest the AGN, but at all distances the transverse intensity profiles of the main jet should be more centrally peaked than those in the counterjet. In contrast, the outer envelopes of both jets should be similar in brightness and in their collimation properties at all distances from the AGN. The current VLA provides tantalizing evidence that the scale on which such effects become apparent is indeed accessible in nearby radio galaxies, but its sensitivity and angular resolution are barely adequate to begin testing these predictions. The sensitivity and resolution of the enhanced VLA, particularly using wide IF bandwidths and the A+ configuration at 6–8 GHz, would transform our ability to test such models by imaging the transverse structures, brightness and polarization symmetries of the inner parts of both the jets and the counterjets in nearby low-power radio galaxies. (Sensitivity is critical because the best diagnostics require accurate measures of the degree of polarization in the fainter, counterjet, emission).

A second way to test the decelerating-jet picture for nearby galaxies is to look for evidence for the entrainment in the distribution of Faraday depth along the jet, *i.e.*, as a function of distance from the AGN. (The internal Faraday depth in an entraining jet may be almost independent of distance from the AGN, whereas that in a jet that is not entraining declines rapidly as it spreads.) We know from observations with the current VLA that the Faraday-thick regime in most such jets is below 2 GHz, and in many it must be below 1.5 GHz. Sensitive polarimetry with enough resolution ($\leq 1''$) to distinguish jets clearly from their surroundings below 1.5 GHz is needed to explore this possibility. The 0.6 GHz system at the highest possible angular resolution (A+ configuration) would be the best hope for adding this diagnostic to the repertoire of probes of jet dynamics in galactic atmospheres.

High power sources: high-velocity "spines"?

In radio-loud quasars, one jet is usually much brighter than the other until the terminal hot spots (tens or hundreds of kiloparsecs from the AGN). The kiloparsec-scale jets are not as prominent as those on the parsec scales however, suggesting that the emission is dominated by flows with relatively low Lorentz factors (~ 2). Some parameters of quasar hot spots (compactness, location) also depend on whether they are on the side of the brighter jet. This is remarkable because jet deceleration should be mediated by a sequence of oblique shocks in such powerful sources. Candidates for such shocks are indeed present in the regular patterns of bright knots along many quasar jets. One way to preserve bulk relativistic motions as far as the hot spots is for *part* of the flow to have very high Lorentz factors. This suggests that jets in Fanaroff-Riley Class II (FR II) sources may also contain a range of Lorentz factors at any distance, in this case a high-speed spine being essentially invisible until the end of the jet while most of the observed jet emission comes from a lower-speed boundary layer, or sheath. Once again, we must resolve the *internal* structures of the jets to test this hypothesis. This is difficult because the jets in FR II quasars and radio galaxies are much better collimated than those in weaker sources, those in the FR II radio galaxies also being relatively faint. Resolution increases of at least a factor of two to three beyond those in the A configuration are necessary, even for the nearest FR II sources. These must be complemented by matching sensitivity increases (preserving surface brightness sensitivity), especially for polarimetry. It is particularly important to learn whether the radio jets are truly center-brightened, or whether we are observing only the outer, slower parts of the flow. These issues require transverse resolution of the jets in FR II sources with a representative range of source powers, and will best be approached with resolutions of $0.1''$ or better in the A+ configuration at 8 GHz.

Particle acceleration

Are particles being accelerated in the jets, and if so how? To answer these questions, we need to obtain the radio spectra of jet substructures such as knots and hot spots. This requires multi-frequency imaging with scaled arrays at resolutions beyond what is now possible for most FRII's. Scaled-array observations, which are essential for reliable spectral imaging, are limited to about $1.2''$ resolution with the current VLA. This is inadequate to resolve shocks and boundary layer features in any but a few nearby jets. We need to push the scaled-array capability to higher resolution without losing sensitivity at the higher frequencies. This requires the A+ configuration and the sensitivity improvements expected from the broader bandwidth (used in a spectral line mode to minimize bandwidth smearing for wide-field observing).

Stability and confinement

The mechanisms for stabilizing and confining radio jets are unclear. The jets contain magnetic fields that are often well-ordered but it is unclear whether these fields actively influence jet dynamics. Progress in understanding jet stability depends on knowing what aspects of the flows are visualized through their synchrotron radiation. Once the previously-mentioned rôles of relativity and particle acceleration in controlling the *appearance* of the flows are determined, the ability of an expanded VLA to measure the spreading rates of jets in powerful (FRII) radio galaxies and quasars will be an important factor in understanding jet stability and dynamics. There have also been hints of rotation measure gradients across some jets (*e.g.*, that in NGC6251) in regions where their collimation properties change. Such gradients—a possible signature of magnetically-assisted collimation—are difficult to detect with the limited resolution and sensitivity of the current VLA. This arena of high-resolution polarimetry will be transformed by the combination of the A+ configuration and wide bandwidths, and will also benefit greatly from improved sampling in the λ^2 domain provided by a new 2.4 GHz system.

4.4.3 Hot Spots

Hot spots are the supposed termination regions of jets and may be sites of extranuclear particle reacceleration in radio sources. There have recently been reports of systematic side-to-side differences between jetted and counterjetted hot spots, particularly in 3CR quasars, including differences in compactness and placement in the lobes, and, most surprisingly, extended regions of somewhat flatter high-frequency spectra around the jetted hot spots. These studies suggest that whatever induces the asymmetry between the brighter and fainter jets in such sources extends at least as far as the hot spots, and perhaps beyond them. If the relativistic-jet model is correct, this implies that some bulk relativistic flow persists into the radio lobes. This greatly increases interest in detailed imaging and continuum spectroscopy of jetted and counterjetted hot spots at high frequencies. The only hot spot structures that have been fully resolved by the current VLA are in nearby radio galaxies such as Cygnus A and Pictor A. To resolve the physically-interesting structures in the hot spots of distant radio galaxies or quasars we must increase the angular resolution beyond that obtainable now with the VLA by increasing the u-v baselines, not by going to higher observing frequencies. Ideally, we need scaled-array capability at resolutions of order $0.1''$ from 0.6 to 40 GHz, with enough sensitivity at the higher frequencies to determine the spectra of the more emission associated with the hot spots. This requires high bandwidth at the high frequencies, and the A+ configuration (plus cross-linking to the VLBA) at the low frequencies.

4.4.4 Lobes of Radio-loud AGNs

Being one of the original problem areas for which the VLA was designed, studies of radio lobes benefit more subtly than other arenas from the proposed VLA enhancements. We note, however, that it now apparent that the lobes of many radio galaxies and quasars are highly filamentary. This increases the need for high-resolution imaging of lobes with good sensitivity. The mechanism for the filamentation, which is very common if not ubiquitous, is unclear. It may be attributable to large-scale (thrashing) instabilities in the jets, to velocity shear in the lobes, or to a variety of thermal and nonthermal cooling instabilities in the lobe plasma. Both (continuum) spectroscopy and polarimetry of the filaments in sources of different powers and in different environments will help to pin down the origin of the filamentation. Contending mechanisms will cause very different effects at high frequencies: if filaments are merely regions of higher field, their spectra will steepen at high frequencies; if they are due to particle acceleration, they should be bright at high frequencies. High-frequency polarimetry with enough sensitivity and resolution to determine the orientations of the magnetic fields within in filaments is also important to understanding the mechanism. To make progress in this arena, sensitive, high-resolution images are needed at both lower, and higher, frequencies than are optimal with the current VLA (4.9 and 8.3 GHz). The A+ configuration is needed at the lower frequencies, and improved sensitivity (increased bandwidth, lower system temperatures) at the higher frequencies.

The depolarization properties of the lobes, which appear to be dominated by a foreground, turbulent magnetized medium around them, offer a probe of the conditions in this medium. The medium is associated with the host galaxy in some cases, with the host cluster in others. The depolarization asymmetries may also help to constrain the inclinations of sources to the line of sight, at least on a statistical basis. Depolarization imaging would be greatly helped by a sensitive 2.4 GHz system (as mentioned elsewhere, the "gap" between 1.5 GHz and 4.8 GHz in the λ^2 space that is relevant to polarimetry is unfortunately large) and for some sources the Faraday-thick regime is evidently below 1 GHz, so the 0.6 GHz system would be valuable. Detailed investigation of the depolarizing medium requires resolution of the intervening screen. This has not been achieved in many cases and for sources with low rotation measures may be contingent on high angular resolution at low frequencies (the A+ configuration).

Some objects, all Fanaroff-Riley Class I (plumed) galaxies, show hints of internal depolarization below 1 GHz. Confirmation of this phenomenon, which is important for testing models of jet deceleration by entrainment, needs sensitive, high-resolution, polarimetry at 1.4 GHz and below and would benefit from the high-efficiency prime-focus feeds. More speculatively, might consider what is needed to detect the intrinsic mass flux of the jets of high luminosity sources, in which the Faraday-thick regime is likely to be $\leq$300 MHz. The A+ configuration at low frequencies offers the best chance to estimate jet mass fluxes directly by detecting internal depolarization of the lobes.

Studies of radio lobes do not drive the VLA Development Plan particularly hard, but they will benefit from improved resolution (A+ configuration), sensitivity and frequency coverage at the lower frequencies and from improved sensitivity and the E configuration (for scaled-array studies) at high frequencies.

4.4.5 Black Hole "Beacons" in Nearby Galactic Nuclei?

Can the VLA detect a radio continuum core in the nucleus of every nearby galaxy? It is crucially important to answer this question because such sources may be beacons marking the locations of supermassive black holes in galactic nuclei. By simply detecting these radio beacons, the VLA can (1) constrain counts of "simmering", rather than "dead", quasars in the local Universe, thereby impacting our understanding of quasar evolution; and (2) provide precise "finding charts" for follow-up dynamical studies of black hole environments with the VLBA and HST.

A radio continuum source can mark nonthermal emission from an active nucleus. These kinds of sources are commonly found among nearby giant elliptical galaxies, with the weakest known radio elliptical being NGC3379. The radio emission from these sources most likely arises from a relativistic jet formed in the vicinity of, and energized by, a supermassive black hole. A radio continuum source can also mark a mixture of thermal and nonthermal emission from a nuclear starburst, which possibly also contains a very weak embedded active nucleus and supermassive black hole. Even the nucleus of our Galaxy, marked by the Sgr A complex and including the enigmatic source Sgr A*, falls into this category, but scaled to a distance of 8 kpc.

The enhanced VLA, with a bandwidth of 2 GHz at λ4cm, could detect *in only one hour* a source like our Galaxy's Sgr A complex, of diameter 16 pc, but at a distance of 20 Mpc. For comparison, the current VLA would require a 10-hr integration. Thus, the enhanced VLA will make it practical, for the first time, to search the nuclei of the more than 100 northern galaxies closer than 20 Mpc for radio beacons as weak and as compact as that in the nucleus of our own Galaxy.

4.4.6 Instrumental Requirements for AGN Continuum Studies

The critical instrumental parameters for AGN continuum studies are a combination of the angular resolution to determine the distributions of total and polarized intensity within jets, around hot spots, and in the lobe filaments of powerful sources, combined with enough sensitivity to image the *polarized* emission. The need for accurate polarimetry of features that may be intrinsically faint or even beamed away from us by relativistic bulk motion drives the demand for sensitivity. Wide bandwidths are not by themselves a panacea for sensitive imaging and polarimetry at the lower frequencies because of bandwidth smearing, Faraday rotation, and RFI. Most wide-band continuum imaging and polarimetry at low frequencies will be done in a spectral-line mode and will need the expanded correlator capabilities.

This arena also benefits greatly from the increased resolution offered at all frequencies by the A+ configuration, and from cross-linking with the VLBA. 0.6 GHz and 2.4 GHz systems will be particularly important for imaging spectral gradients and curvature, and for polarimetry. The E configuration and very low frequencies are relatively less important, though not irrelevant.

4.4.7 Absorption against AGNs

Observations of neutral gas in absorption against the continuum emission of AGNs are a powerful way to study the circumnuclear gas. Limited studies of the gas kinematics on the lines of sight toward compact sources (typically milli-arcsec) have provided some evidence for infall and an estimate of the accretion rate of gas, that might eventually fuel the black hole. If the nuclear radio source is resolved then the rotation velocity of the circumnuclear disk can be measured, providing an estimate of the black hole's mass.

Examples of both kinds of studies exist, but suffer from two major problems. The rotation velocities of the circumnuclear gas are very high, resulting in broad ($\sim$ 1000 km s^{-1}), extremely shallow (peak optical depths $\sim$ 0.005) profiles, requiring a better spectral dynamic range than is generally achievable. Total bandwidth restrictions make it impossible to search at the higher frequencies for molecular absorption covering such large velocities. Another problem (and intriguing possibility) is that large amounts of gas may be locked up in tiny, very cold clouds, which have intrinsic velocity widths of a fraction of a km s^{-1}. Extremely narrow channels are needed to detect those clouds.

The proposed bandwidth and number of channels in the new correlator will alleviate both the velocity coverage problem for molecular studies and the velocity resolution problem for the very cold clouds. A high spectral dynamic range ($\sim 10^4$:1) is also required. The A+ configuration will significantly increase the number of objects against which rotation velocities of the circumnuclear disk can be imaged. The 1.4 GHz extension to lower frequencies increase the number of sources strong enough to be targets for such work.

4.5 CLUSTER ENVIRONMENTS

The intragalactic medium (IGM) in clusters and groups of galaxies is an important large-scale feature of the universe. X-ray observations show us that this plasma, which exists on a scales up to many Megaparsecs, has a significant hot component. Radio observations show us that relativistic particles and magnetic fields can be another important component of the medium in some situations.

The medium is important in its own right as it offers an extreme environment in which to study plasma processes. How ubiquitous are magnetic fields in the IGM? How were they formed? Are dynamo processes responsible? What rôle do they play in so called "cooling flows"? Is the energy density of magnetic fields important relative to thermal gas? How are relativistic particles accelerated and/or re-accelerated on large scales? Are they energetically important? What is the range of temperatures in the thermal IGM and how is it regulated?

But it is also becoming clear that infall of individual galaxies and small groups into bigger clusters and more equal cluster-cluster mergers are both important for galaxy evolution. Studies of clusters at $z > 0.4$ using the Hubble Space Telescope show that galaxy morphology has changed with epoch. The most obvious change over this period is the size of the clusters which have been merging. The further back we look, the smaller the building blocks should be. The rate of such mergers depends on the cosmological density parameter: the number of recent mergers to be expected increases with the density of the universe. The most important changes in the clusters are expected to take place in the IGM. The density of the IGM will, in turn, modify galaxy properties as they pass through it. The system of gas and galaxies is coupled.

The enhanced VLA will be able to study the properties of the IGM in various ways. The nonthermal radio halos found in some rich dense clusters trace a combination of the relativistic particles and the perpendicular magnetic fields. Faraday rotation by the medium between us and the radio sources probes the line-of-sight magnetic field and the thermal electron density. The Sunyaev-Zeldovich effect probes an integral of the thermal pressure along each line of sight through a cluster. The properties of twin jet radio galaxies also probe pressures and pressure gradients in the IGM. Finally, gravitational lenses can be used to estimate the mass along the line-of-sight through rich clusters.

4.5.1 Cluster Radio Halos

Large scale cluster halos are known only in a few nearby ($z < 0.1$) clusters and in a few higher redshift clusters where the emission interferes with measurement of the Sunyaev-Zeldovich effect. The emission seems correlated with high density clusters which do not show cooling flows. This could indicate that the acceleration of the particles is a byproduct of a cluster-cluster merger which has disrupted any cooling flows and generated a lot of turbulence and/or shock where weakly relativistic particles are accelerated to high enough energies to produce the observed radiation. However, in reality very little is known because the emission is known in so few cases and then is hard to observe above 1.5 GHz or in polarization. Most of the reason for this difficulty is surface brightness sensitivity.

The enhanced VLA should correct this by dramatically improving the continuum sensitivity (especially above 1.5 GHz) and the surface brightness sensitivity using the E configuration. This improvement should allow us to detect halo emission, if present, in many more clusters and lower density regions in poor clusters and the surroundings of rich clusters. It also will allow the study the extent, structure, polarization and spectrum or radio halos, all of which are needed to constrain theories of its origin. This emission seen at higher redshifts may also be the signpost of recent merger activity.

4.5.2 Faraday Rotation

Faraday rotation, which gives us the vector integral of $n_e\mathbf{B.dl}$ along the line of sight, is another important probe of the IGM. Work to date has shown us that the centers of cooling flow clusters have surprisingly large magnetic fields. Allowing for the uncertainties of the number of field reversals along the line of sight, the magnetic energy density in these regions could easily be as high as the thermal energy density. The structure of the field is probably very complex and is consistent with predictions of dynamo models.

The enhanced VLA will open up new parts of parameter space for such studies. At high frequencies, the increase in sensitivity will let us probe sources in clusters which so far are completely depolarized. These sources may have extreme rotation measures for which the differential rotation over the synthesized beam or across the observing band completely depolarizes the emission.

Adding the 2.4 GHz band will allow smaller Faraday rotations to be detected by providing a critical part of λ^2 space between 1.4 and 4.9 GHz.

Finally the increased sensitivity and the expected improvement in the systematics caused by the IF system of the current VLA should allow many more sources to be studied in Faraday rotation. This will allow much more complete imaging of the Faraday rotation along different paths through a cluster.

Imaging both the diffuse radio halos and the Faraday rotation seen through different parts of clusters should give us a clear picture of the importance of magnetic fields in clusters of galaxies and at a wide variety of different densities. This will be a major contribution of an enhanced VLA to extragalactic physics.

4.5.3 The Sunyaev-Zeldovich Effect

The Sunyaev-Zeldovich effect is also an important probe of the cluster medium. The scattering of the 2.7K background radiation by the hot gas in the cluster gives a negative brightness signal proportional to the integral of $n_e T dl$ where n_e is the electron density, T is the temperature of the hot, thermal gas, and l is the path through the cluster. This gives us an important second integral in addition to the X-ray free-free and line emission through the cluster. This allows one to construct much more complex, realistic models of the cluster density and temperature than is possible using just the x-ray observations. If clusters prove not to be too pathological, it also allows a direct distance measurement which potentially can yield both H_0 and q_0 from several such measurements.

Measuring the Sunyaev-Zeldovich effect is at the limit of the current VLA's capabilities. The enhanced VLA will make such work straightforward, especially in the cores of dense clusters. Other instruments, *e.g.*, the MMA and the specialized array being proposed by Caltech, may be more sensitive to the Sunyaev-Zeldovich effect, however. Even so, the VLA will still serve the critical rôle of determining the distribution of confusing sources which must be subtracted from lower resolution images. The contribution of any radio halo emission in a target cluster must also be imaged as a function of frequency and, if necessary, corrected for. The enhanced VLA will be unparalleled for this. The VLA cannot now image fast enough or at the right frequencies for this task. Without the improvements to the VLA, whether or not the other instruments are built, the Sunyaev-Zeldovich measurements will not reach their full promise.

4.5.4 Radio Galaxies in Clusters

The structures (bends) in twin-jet radio galaxies are sensitive to the thermal and dynamical pressures exerted by the IGM regardless of X-ray detection limits. The bending and distortion of radio tails in rich clusters is likely due to winds in the cluster gas, some of which may be initiated by cluster-cluster mergers. Some sources are found away from the centers of rich clusters where no X-rays are seen. These sources can be used to probe densities below the X-ray sensitivity limit. Both types of observations are surface brightness limited. An enhanced VLA will extend our ability to trace the distortions and the outlying sources in clusters and thus give a more complete picture of the IGM. The increased bandwidth, lower-noise receivers and the E configuration are important to such studies.

4.5.5 Gravitational Lensing

The enhanced VLA should allow measurements of cluster masses using gravitational lenses. Recent optical imaging of the lensing field of rich clusters suggests that rich clusters have deeper central potential wells and a more extended large scale gravitational potential than was previously thought.

These results are limited by uncertainty in the distances of the objects being lensed and by knowing how much of the extension of the objects is produced by the lens and how much is intrinsic. The results suggest a new picture of clusters in which magnetic fields and relativistic particles could be important to their pressure balance.

Radio astronomy has contributed little to such work so far because the VLA currently lacks the sensitivity to image enough objects in each field. We need more sensitive imaging in the VLA A configuration over wide fields at λ20cm of sources in the 10 to 100 μJy range. The improved bandwidth and receiver performance of the enhanced VLA, along with the narrower channels and reduced systematics, should enable the required sensitive wide-field imaging.

4.6 OBJECTS AT HIGH REDSHIFT

Possibly the most exciting areas for research with the enhanced VLA are the evolution of galaxies with redshift and related questions about the epoch of galaxy formation and the detection of protogalaxies.

For many years we have known that the radio source population evolves with cosmological epoch. In particular, the density of sources increases rapidly with redshift. This seems to be true for other types of AGNs as well such as optically selected, often radio weak or silent, QSOs.

Optically, we find that only a little below the 3CR flux limit, most sources are at high redshifts, $z \geq 1$ and often as high as $z = 3$ to 5. Before 1988 we had little information on galaxies in the early universe. Since then there has been an explosion in the number of stellar systems known at high redshift, with almost 100 galaxies now identified at $z > 2$, and about 10 at $z > 3$, corresponding to an epoch when the universe was only about 10% its present age. Most of these galaxies are identified with powerful radio sources although some high redshift galaxies have been identified via their infra-red emission and others have been found associated with quasar absorption line systems.

Many of these systems display characteristics expected for young galaxies ($\leq 10^7$ yrs) undergoing a massive starburst, including: halos of ionized gas up to 100 kpc in extent, dust masses in excess of 10^9 $M_\odot$, and flat optical spectral energy distributions indicative of a young stellar population. Star formation rates in excess of 10^3 $M_\odot$ yr^{-1} have been inferred for some systems.

As mentioned earlier, the HST has been imaging clusters of galaxies beyond $z = 0.4$ and finding evidence confirming the Butcher-Oemler effect, the blueing of cluster galaxy populations with redshift, is related to increased star formation in clusters with redshift. The HST data also show that galaxies themselves have different shapes as we look further back.

Direct observational study of the evolution, and possibly of the formation, of galaxies is clearly becoming possible. The enhanced VLA could play a very important rôle in this exiting arena.

We discussed one key investigation already—a deep H I survey to examine the evolution of gas content of galaxies out to $z \sim 1$. Four other areas of study could be transformed by the enhanced VLA:

1. the study of radio source populations with epoch.

2. observations of molecules, free-free emission and dust as their spectrum is redshifted into the VLA wavelength window.

3. the study of starburst galaxies at high redshifts

4. the study of magnetoionic media (magnetic fields and Faraday rotation) at high redshift.

4.6.1 Source Populations

The history of radio astronomy has been one of ever increasing sensitivity averaging about an order of magnitude per decade. The most sensitive observations with the current VLA reach levels of the order of 10 μJy in selected regions and about 1 mJy over the whole sky, or one to two orders of magnitude weaker than any other radio telescope. A wide variety of sources are observed at all flux density levels including radio galaxies and quasars, BL Lac Objects, Seyfert and other star forming galaxies, low luminosity AGN and normal galaxies. Each population has its own luminosity function which may evolve independently with cosmic epoch.

The enhanced VLA promises to continue this process reaching the 1-μJy level for the first time. As we have probed deep we have found new populations of sources, most recently the apparent domination of starburst galaxies below 1 mJy. It seems quite possible the universe will change again when we probe the next step deeper.

However, what we predict most clearly is that we will be able to study the changes in the properties of the currently known populations with epoch. It seems very likely that these changes are related to the other properties of the universe which are different at earlier epoch such as the clustering environment. In particular, it is important to look for changes in the environments of Fanaroff-Riley I and II radio galaxies with epoch. Does the change in morphology occur at the same luminosity at earlier epochs? Does the cluster environment of the different types of sources change? Is there an epoch at which the morphological classes no longer divide in this way at all, like the changes HST sees optically?

Thus we want to study samples of radio galaxies which in areas of sky that will be studied intensely at other wavelengths. We want to make high quality images, not merely detections, of these sources. For sources below the Fanaroff-Riley I/II break, radio and optical work are now practical to $z \sim 1$. With the enhanced VLA, planned space missions in the IR and ground-based millimeter and sub-millimeter instruments like the MMA, it should be possible to reach $z \sim 3$ for these radio luminosities.

Another example of such a study is the properties of the radio quiet quasars. Although the first quasars were discovered as a result of their strong radio emission, subsequent observations have shown that quasar radio emission is bi-modal with only a small fraction, of the order of 10-15% of optically selected quasars found as strong radio sources with 5 GHz radio luminosity greater than 10^{25}W Hz^{-1} or a ratio of radio to optical luminosity greater than 10:1. Understanding the relation, if any, between the radio loud and radio quiet quasars has been a challenging problem of contemporary quasar astronomy.

Only the VLA has been able to even detect the weak radio emission from the radio quiet quasars, and only from the nearest ones. The greater sensitivity of the enhanced VLA will let us explore the lower end of the radio quiet luminosity function out to greater redshifts where the quasar population density rapidly increases and to determine whether indeed there is a population of truly radio silent quasars.

We want to image these objects and understand their relation to nearby objects like Seyfert galaxies and the nature of their changes with epoch. How do these objects fit into the changes in clustering properties with redshift? Does their radio structure indicate they smoothly join with the properties and Seyferts or do they have radio structures which indicate they are related to the Fanaroff-Riley I's or II's as seen at high z? The key here is the increased sensitivity that will allow high quality imaging of these weak sources at reasonably high redshift.

The tremendous increase in sensitivity at the short centimeter wavelengths also offers the possibility of surveying large parts of the sky at these frequencies. At 30 GHz a survey as deep as the current λ20cm D-configuration (NVSS) survey could be made to the same limiting flux density in the same length of time ! The telescopes would have to be continuously scanned rather than tracking one spot and correlator dumps would be necessary every 0.05 seconds. Alternatively, much deeper surveys of much smaller regions could be made. We know we would find large numbers of steep spectrum sources, as have been cataloged at λ6cm and longer, and probably populations of faint flat spectrum QSOs; however, based on surveys at other wavelengths it is likely that other sunrises would await such studies.

4.6.2 Molecules, Dust and Free-Free Emission

With the discovery of dust and CO emission at $z > 2$, it is clear that a part of the electromagnetic spectrum and the associated physical processes is likely to be visible at the VLA's operating wavelengths. The enhanced VLA would provide almost complete wavelength coverage between 4.5 and 50 GHz, as well as much improved system temperatures and bandwidth. This upgrade combined with the existing large collecting area is just what is needed to study thermal continuum and dust emission at high z, as well as molecular lines as they are shifted into the VLA window.

In the cm-wavelength continuum, the VLA is now primarily sensitive to synchrotron emission for the dusty, star-forming galaxies. In the galaxy rest frame somewhere shortward of a few mm, dust emission dominates the spectrum. In between the long wavelength synchrotron emission and the short wavelength dust spectrum, free-free emission should dominate, possibly between 40 and 100 GHz. This free-free emission as well as the tail of the dust emission should be shifted into the VLA window as z increases.

IRAS revealed a large number of exceptionally luminous galaxies, and made the starburst phenomenon a commonplace of astrophysical discussion. The most direct and reliable estimate of the star-formation rate in these systems is the high-frequency radio emission from the ionized gas, since that is unaffected by the strong dust absorption expected in these systems. Combining this with lower-frequency measurements gives the ratio of synchrotron to thermal emission, itself an indicator of the high-mass end of the initial mass function; comparing this with more quiescent galaxies tells us whether starbursts preferentially form high-mass stars, as might be expected if the star-forming gas is exceptionally turbulent. Resolving the thermal radio emission also gives the physical scale of the starburst. Clearly one wants sensitive, multi-frequency observations both to detect the thermal emission, and to determine where the thermal/synchrotron break occurs in these sources. A reasonable starburst would have an intrinsic thermal luminosity of 10^{21}W Hz^{-1} (100 times stronger than a typical, normal galaxy); this corresponds to 10 Jy at 1 Mpc, or a few μJy at $z = 1$. 40 GHz is redshifted at $z = 1$ to 20 GHz, so this is a strong argument for the highest possible bandwidths at and above 15 GHz: the experiment would still take about 12 hrs, but the possible payoff is tremendous.

At $z \geq 3$, dust emission at 200 GHz is shifted to the enhanced VLA bands. These high-redshift galaxies have been detected in CO with incredibly high estimates of the gas mass ($10^{10} - 10^{12} M_\odot$); the dust reservoir accompanying the gas (itself with a mass of $10^8 - 10^9 M_\odot$) is observable by its thermal emission in many high-redshift galaxies and QSOs. The MMA will be the best instrument for detecting the dust at higher frequencies, but the VLA's 50 GHz limits or detections would be valuable both in looking at the coldest dust, which may not emit at all at higher frequencies, and in determining the spectral shape at relatively long wavelengths. The former is important to estimating the *total* (rather than just the warm) dust mass, while the latter constrains the microscopic properties of the dust. Further, the dust-ionized gas break in the spectrum could only be observed with the enhanced VLA. This would be a tough but do-able experiment: $10^9\ M_\odot$ of dust, corresponding (with local gas/dust ratios) to $10^{11} M_\odot$ of hydrogen, would show up at about $10(T_{\rm dust}/50\ {\rm K})$ μJy at $z = 3$. This would take 12 hrs with the proposed upgrade, or 1.3 hrs with the super-wide 10 GHz bandwidth, for a 5σ detection. Again this argues strongly for the highest possible sensitivity at frequencies above 20 GHz, as well as high resolution to image the dust.

Detections of CO emission at high redshift have been reported for about ten objects. Of these, the strongest lines have been observed from the infrared luminous source IRAS FSC10214+4724 at $z = 2.3$, and the lensed quasar known as the Cloverleaf at $z = 2.5$. Other detections include radio galaxies and damped Lyman-α systems. For all detections the inferred mass of molecular hydrogen is in the range 10^{10}–$10^{12} M_{\odot}$.

Although the nature of the sources is not clear and may well exist in great variety, it is clear that there is an abundance of molecular gas at high redshift. These gas-rich systems present us with examples of various stages of galaxy formation and evolution that can be imaged. Because the emission is in spectral lines, it carries all the usual spectroscopic information, most notably, information about the kinematics. Radio spectroscopy is not only uniquely capable of observing the molecular gas that dominates these systems, in doing so it provides a wealth of information.

The task of studying the high redshift molecular line sources falls most naturally to the Millimeter Array. From what little is known about the temperature in the sources, higher lying rotational lines are expected to be stronger, so that even at the observed redshifts these fall in the millimeter bands. However, the CO transition at 115 GHz has been detected in FSC10214 and should be observable with an enhanced VLA in many sources. It should also be mentioned that models of early universe chemistry indicate that molecular oxygen may be more abundant than CO. The enhanced VLA will be used to determine the mass in O_2 from observations of the redshifted 60 GHz line and, for $z > 1.4$, of the redshifted 119 GHz line. Together with the CO observations, the results on O_2 would allow direct tests of chemical evolution with cosmic epoch. The contribution of the enhanced VLA, beyond the detection capability (which the Green Bank Telescope will also provide), will be to image the lines so that their kinematics can be determined from both spatial and velocity structure.

The VLA Development Plan must address two basic requirements for these observations. First, low noise receivers are needed for continuous frequency coverage from 20–50 GHz. This provides complete coverage for redshifts $z = 1.3$ to 4.8 for the CO(J=1→0) transition at 115 GHz and for redshifts $z = 0.16$ to 4.9 for one of the O_2 lines. Second, the correlator must have a minimum bandwidth of 500 MHz. The lines can be wide; 1000 km s^{-1} full width is not unreasonable. With an equal amount of baseline, that translates to over 300 MHz bandwidth at 50 GHz observing frequency. Uncertainties in the redshift and the fact that the gas need not have the same exact redshift argue for 500 MHz as the required bandwidth. For searches in redshift even more bandwidth is necessary.

As an example of the enhanced VLA capabilities for imaging these sources, consider the following: a CO(J=1→0) line strength of 3 mJy peak and a full width of 800 km s^{-1} spread over an area of diameter $6''$ at $z = 2.3$. With 100 km s^{-1} channels in 12 hrs in the D configuration, the enhanced VLA would achieve 15:1 signal-to-noise per channel at $2''$ resolution on the line peak. If the emission is more peaked spatially or spectrally, higher spatial and spectral resolution will probably also be useful.

As more high redshift objects are found, the enhanced VLA and the MMA together will allow us to construct a complete picture of the physical conditions in dusty, otherwise, obscured objects. This is an entirely new astrophysical arena which the enhanced VLA and the MMA will open up together.

4.6.3 Starbursts at High Redshifts

The bluer populations of galaxies reported many years ago by Butcher and Oemler and the recent HST images of these clusters suggest that more star formation has gone on in the past in rich clusters. Higher redshift HST images of the cluster around 3C324 at $z = 1.2$ suggests that even more activity is occurring at this epoch. The well-known relation between radio continuum emission and far IR dust emission shows that star formation and centimeter continuum emission are closely linked. Thus using the signature of star formation we can probe the recent activity level in distant rich clusters in the radio. However, to reach the necessary radio luminosities we are limited to

$z \sim 0.4 - 0.5$ now. The enhanced VLA will be able to reach these same luminosities at $z \sim 1$, increasing the look-back time from about 50% to about 75% of a Hubble time. ($q_0 = 0.5$)

4.6.4 Faraday Rotation

Recently, two radio galaxies with $z > 3$ have been shown to have large Faraday rotation in their rest frame. The magnitude of the rotation measure is similar to that in nearby cooling flow clusters. These radio galaxies may be located in the centers of similar dense clusters, or the environments of more isolated systems at high redshift may enveloped in a strong magnetic field. Current arguments suggest that very massive clusters would not have formed at such high redshifts, so the second possibility may be favored. In this case, magnetic fields may play an important part in galaxy formation.

Our study of this phenomena is limited by the decrease in the rest frame Faraday rotation by $(1+z)^2$. The 2.4 GHz band is important to provide the frequency coverage to measure the reduced rotation measures. Sensitivity is important because of the low net polarizations from these sources. Resolution plus sensitivity is also critical to prevent the change in rotation measure across these sources from canceling out the polarization signal. Of course, the more resolution we have the more we can learn about the geometry of these fields. Thus once again polarization and the upgrade are important to studies of magnetic fields in high-z objects.

Chapter 5

TECHNICAL ISSUES AND BUDGET

5.1 INTRODUCTION

This Chapter discusses tradeoffs between the requirements of different astronomical problems, and some engineering difficulties, that must be resolved to settle the design, cost and (in some cases) the schedule of the project.

5.2 ANTENNAS AND RECEIVERS – TRADEOFFS

5.2.1 Polarization vs. Wide Bandwidths

The design of feeds and receivers which support observations over large bandwidths requires either the use of linearly polarized feeds or of circularly polarized feeds with compromises made on polarization purity. The typical cross-polarization performance of wide bandwidth circular polarizers, shown in Fig.5.1, is two or three times worse than for the current narrow bandwidth polarizers. Linearly polarized feeds would give better sensitivity and lower cross-polarization. Their main disadvantages are: the need to calibrate the relative amplitude and phase of the two polarizations accurately, the difficulty of analyzing the data when parallactic angles differ at the ends of long baselines, and the fact that their performance for total intensity measurements degrades less gracefully than for circularly polarized feeds if one polarization channel malfunctions.

The VLA now uses circularly polarized feeds. The accuracy of polarization measurements is limited not by the absolute value of the cross-polarization, but by its time variability. It would be unwise to increase the cross-polarization significantly until the cause of the time variability in the existing VLA systems is understood. The tradeoffs between using linearly and circularly polarized feeds for the new wide-band systems therefore require careful study.

5.2.2 Spillover

With the completion of the 1.4 GHz band upgrade in 1994, ground pickup at low elevations became a significant problem. The 1.4 GHz feed should be redesigned to eliminate spillover problems. There is also keen interest in observations at lower frequencies in the 1.4 GHz band. The extent to which the 1.4 GHz band may be extended and improved without eliminating or seriously compromising

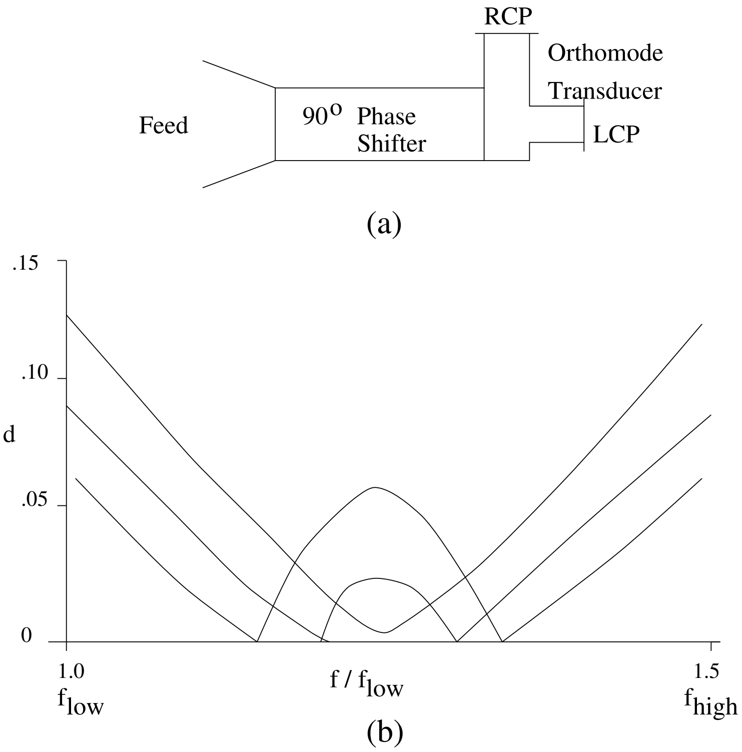


Figure 5.1: (a) Schematic diagram of circular polarizer. (b) Typical variation of the cross-polarization voltage ratio, d, across the band. Typical curves for three different phase shifter designs are shown.

other systems on the feed ring (*e.g.*, the 2.4 GHz band system that is also scientifically attractive) or at the prime focus must be considered carefully.

The best way to improve performance in the 1.4 GHz band alone would be to install a larger subreflector, similar to that used for the VLBA. This could provide good performance at a lower frequency for the same size feed mouth as at present. But this option is expensive and introduces compatibility problems for all feeds, especially at the prime focus (see Sec.5.2.3). In principle, the 1.4 GHz band can be extended down to 1.2 GHz with a new high-performance feed at the Cassegrain focus, illuminating the current subreflector. This approach would however require a long, geometrically awkward feed with an expensive and heavy lens, without which the feed would extend through the vertex room floor. A solid dielectric lens would weigh about a couple of tons; a compound lens such as that on the present feed would not be broad-band, though it is unclear how far such a design could be pushed. It will be important to assess how the performance of any proposed system degrades below 1.2 GHz, as reasonable performance down to about 1050 MHz might reduce the need for the most problematic prime-focus system (800-1200 MHz),

5.2.3 Prime Focus Systems vs. Cassegrain Performance

To observe at frequencies above $\approx$ 400 MHz requires modifying the quadrupod and focus-rotation mount (FRM) if high performance is desired. The reason for this is illustrated in Fig. 5.2 which shows that the subreflector support structure currently blocks the prime focus. Obtaining access to the prime focus by retracting the subreflector requires lengthening the legs of the quadrupod.

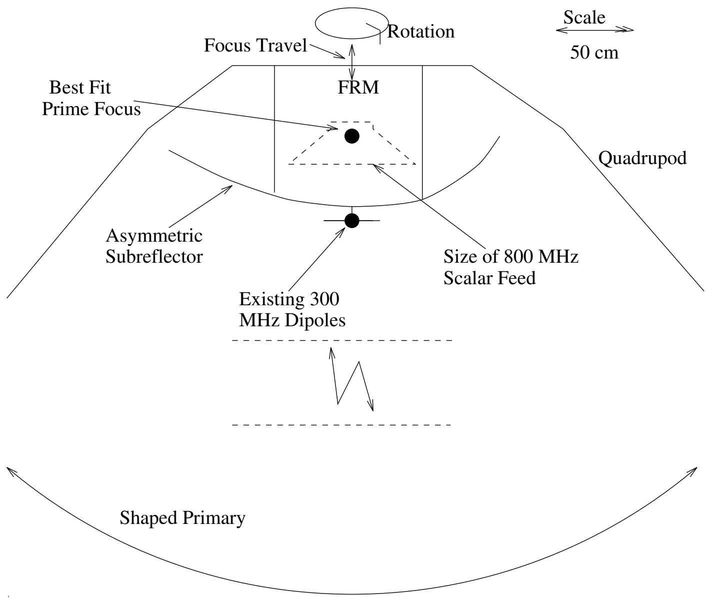


Figure 5.2: A sketch, approximately to scale, of the prime focus region of the VLA antenna.

The FRM must then be modified to position the subreflector to illuminate the Cassegrain feeds optimally. The only way to avoid this with the present subreflector is to accept the poor beam shape and reduced aperture efficiency associated with operating the feed at an out-of-focus position, as we do now.

Other options that might be considered to expose the prime focus include shifting the subreflector laterally, tilting it to one side; or, if the subreflector is rebuilt, having it open like a clam shell. (The last approach may be the only practical way to operate at the prime focus if a larger subreflector is used to extend the 1.4 GHz band down to 1.2 GHz.)

The 800–1200 MHz system may be the most problematic. Because of the size of the feed, it must be located at the prime focus. Design of an *efficient* feed at the prime focus is hampered by the shaping of the primary reflector (which departs from a true paraboloid by about 1 cm, so there is no exact prime focus). To avoid interfering with observations in other bands, the feed must be removable. One idea is to stow a scalar feed against one leg of the quadrupod, swinging it into place when needed. There are concerns, however, about the mechanical complexity and maintenance of such a system.

Another concern is that prime focus systems are somewhat more susceptible than Cassegrain systems to interference from low-elevation sources. This may become more important in the presence of an ever-worsening RFI environment (see §5.6).

At issue is which options offer the best scientific return without seriously compromising the performance at other frequencies. The present 75 MHz and 327 MHZ feeds may raise the system temperature at L Band by about 10% (the magnitude of the effect is not well-determined). This effect may be present for the proposed prime focus systems at all bands, and is likely to depend on frequency in a complex manner.

A related issue is whether to pursue high-efficiency performance at the prime focus at all. Fig. 5.3 compares the proposed enhanced frequency coverage for the VLA with that of other large interferometers and single dishes. The GMRT in India, and the WSRT in the Netherlands, will provide coverage in the frequency bands of interest, albeit with reduced sensitivity or narrower

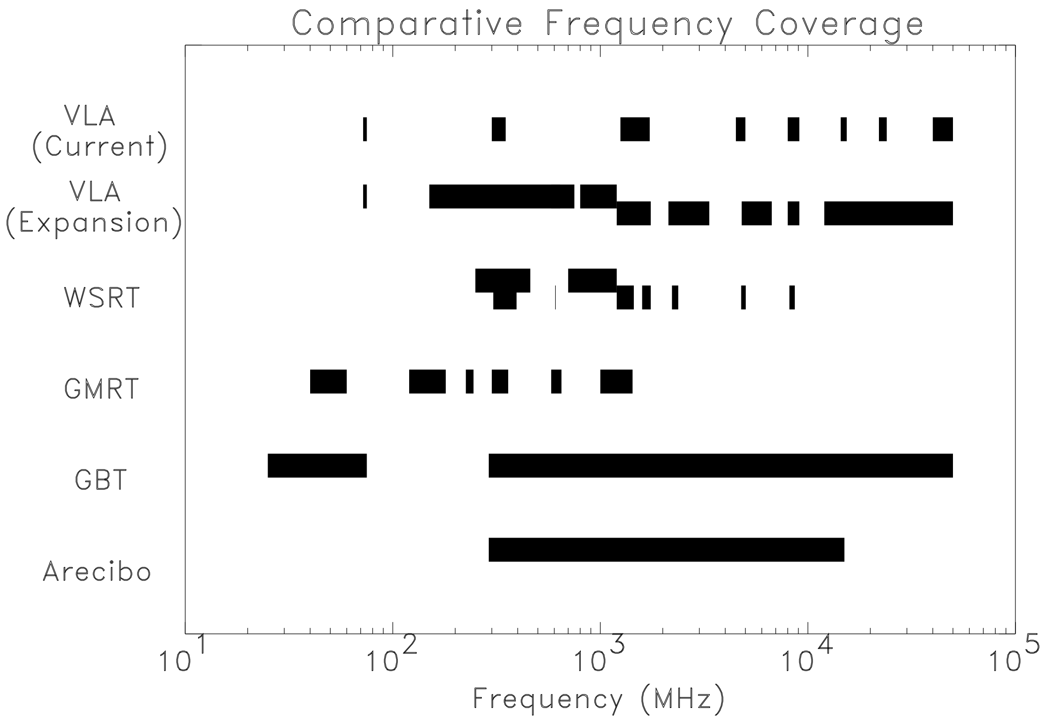


Figure 5.3: The frequency coverage of large interferometer arrays and single dishes compared with the current VLA and with the proposed VLA enhancements.

bandwidths. The GBT and Arecibo will provide a single dish capability over the frequency range of interest with good sensitivity.

An alternative to prime focus operation at the VLA may be to build inexpensive wide-band antennas (*e.g.*, log-periodic arrays) to support some low frequencies separately. Such a stand-alone antenna system, sharing access to the I.F. transmission system and the correlator for simultaneous observations with the VLA paraboloids, has previously been proposed for 74 MHz. It may be appropriate to identify what *range* of observing frequencies could be better served by such an array than by working at the prime focus, and at what cost. For 74 MHz, antenna tolerances can be met cheaply because the wavelength is so long (4 m). At higher frequencies, more costly and more numerous antennas would be needed to sample the shorter u-v spacings (or the antennas would need to be transportable). The cost and effectiveness of such options (as a function of frequency) should be weighed against that of prime focus operation, but it seems unlikely that that they would help the most difficult (800–1200 MHz) case at reasonable cost.

The difficulties of operating prime focus systems between a few hundred and 1200 MHz without degrading the Cassegrain performance emphasize the need for knowing more about VLA's RFI environment (see §5.6). Improved RFI statistics might help to define the most appropriate band edges.

5.2.4 Antenna Modifications

To add 2.4 and 33 GHz observing bands at the Cassegrain focus we must rearrange the feeds on the VLA feed ring and install a new feed enclosure. A structure more like the VLBA feed cone will likely be used. Support of multi-band performance (§1.2.6) would entail additional modifications.

Modifications to the antenna quadrupod and FRM are needed to support the proposed higher-efficiency prime focus systems: the 600 MHz system, a broadband UHF system, or a cooled 800-1200 MHz receiver. For the first two options, the quadrupod must be lengthened to allow siting these systems at the prime focus (at present, the 330 MHz feed is $\approx 0.5\lambda$ out of focus). For the 800-1200 MHz system, we need to study how to optimize the desire for sensitivity (*e.g.*, to search for redshifted HI in emission or absorption) versus the added weight of a refrigerator. Lightweight (Sterling) refrigerators will alleviate the problems. The effect of modifications to the quadrupod structure and the FRM, together with the weight of a feed and cooled receiver, could conceivably cause excessive gravitational deformation of the primary reflector. This must be checked by structural analysis.

Performance in the 40–50 GHz band requires some effort to improve the surface quality, pointing accuracy, and tracking accuracy of the antennas that are not now outfitted for this band. The methodology for measuring and adjusting the primary reflectors is now well understood.

5.2.5 A Robust Total-Power System

A fast and accurate means of measuring the total power is needed. In recent years, mosaicing has been used often and successfully at the VLA to image fields of view comparable to, or larger than, the primary beam of the antennas. To measure the visibilities for the smallest u-v separations required in mosaiced images, we need total power measurements with single antennas. These could be made with the VLA antennas by scanning rapidly across the region being imaged and adding the “single-dish” information to the interferometer data. This capability requires a stable total power system for each antenna and some on-line and off-line software development.

A second reason for a robust total power system is for observing transient phenomena which can significantly change the system temperature over short timescales. An outstanding example is that of solar flares, which can change the system temperature by an order of magnitude in a few seconds.

5.2.6 Multi-band Performance

For some experiments, multi-band performance is highly desirable. For example, transient phenomena on the Sun and stars would benefit greatly from simultaneous measurements in two or more bands. One possibility is to support dual-frequency measurements in the 2.4 and 8.4 GHz bands and/or dual-frequency measurements in the 4.9 and 15 GHz bands. An additional benefit of dual-frequency observing is that one of the two bands in a given pair could be corrected for the long-standing problem of beam squint, caused by the VLA asymmetric geometry, through the use of a tertiary mirror.

A practical benefit of dual-frequency observing is that the lower frequency of a given pair can be used to track the phase variation of the atmosphere, from which corrections can be derived and transferred to the high frequency. Implementation of such a scheme will be considered for enhanced high-frequency performance at the VLA.

In the case of solar observing, an alternative to multi-band performance is “frequency-agile” performance using a low-performance (helical or log-periodic) feed at the prime focus.

5.3 IF TRANSMISSION SYSTEM

The details of the IF channelization are still to be decided. A possible design has the ~2 GHz of instantaneous bandwidth broken into 2 pairs of oppositely polarized IF channels, each 500 MHz wide. The two IF channels in each polarization need not be contiguous in frequency. At higher frequencies, where much more than 1 GHz of receiver tuning range is available, four different frequencies could be observed simultaneously. For full flexibility, this scheme will require 4 synthesizers per IF conversion in each antenna, and will return 4 independent IF channels to the correlator. It is possible that the number will be further upgraded, to 8 independent IFs. To avoid serious bandwidth smearing of the maps the widest bandwidth to be correlated will probably be no more than a few ×100 MHz.

Analog transmission is preferred for the simplicity of the equipment at the antennas. Stability of the frequency response may drive us to the use of digital transmission, especially on runs longer than 20 km. Further study, including laboratory testing of a fiber link, is required. As well as increasing the instantaneous bandwidth, this new system will strive to provide better bandpass stability leading to better spectral dynamic range.

The antennas in the Pie Town and Los Alamos "rings" must be connected to the VLA by wide-band data links. Many technical and economic aspects of the long runs of optical fiber being contemplated for this, as described in §1.2.5, require detailed study before the cost and feasibility of the A+ configuration can finally be assessed.

For links that the NRAO might install and use on an exclusive basis, we need to explore the cost of obtaining right-of-way and of installation (estimated as about $5 per foot, considerably more than the cost of the fiber cables themselves). The main technical issue for such links would be the stability of the frequency response of the IF channels; this should be evaluated over a link to the Pie Town VLBA antenna as soon as possible.

The proposed links to Bernardo and to the "Los Alamos ring" antennas are unlikely to be economic to install and operate on an exclusive basis. It may however be practical to lease long wide-band fibers and suitable booster amplifiers from commercial carriers when these links are needed for A+ configuration operation. The NRAO should plan to get early experience in using commercial fiber links for real-time interferometry using the nearer VLBA antennas. The commercial-link environment should be simulated using a fiber to the Pie Town antenna as soon as possible.

It will be important to evaluate the logistical and technical problems of using commercial fiber before the feasibility and operating cost of the full A+ configuration can be determined. If commercial links can be used successfully, however, this approach may be extensible beyond the baselines considered here as part of the A+ configuration, *e.g.*, to Kitt Peak and Fort Davis.

The final locations for the A+ configuration antennas should be chosen by combining the above factors with the need for good imaging properties when the antennas are used with both the VLA and the VLBA. These areas require further study, which should begin as soon as possible.

5.4 CORRELATOR DESIGN

The current VLA correlator is limited to a bandwidth of 4×50 MHz. A new correlator is needed to process the ~ 2 GHz of bandwidth and to achieve the increase in continuum sensitivity and instantaneous spectral coverage. Moreover, the current correlator limits the type of science which can be done due to its limited spectral resolution at wide bandwidths. With a 50 MHz bandwidth now, the VLA can only produce 8 (Hanning smoothed) spectral channels in total. With so few channels, wide-field imaging at low frequencies, and searches for redshifted spectral lines (*e.g.*, H I) are extremely inefficient. Similarly, a 50 MHz bandwidth at high frequencies (*e.g.*, 350 km s^{-1} at

43 GHz) makes observations of radio recombination lines difficult, if not impossible. It also excludes many components of those molecular lines which are split into multiple transitions.

Current specifications for the new correlator are demanding:

- **Bandwidth and IF Channelization**

  Current specifications call for processing 1 GHz of IF bandwidth in two orthogonal senses of polarization. The cost of the digital part of the correlator is minimized if the band is subdivided before digitization, but this increases the cost and complexity of the analog part. There is some number of baseband channels, presently undetermined, that will minimize the cost. It appears that the minimum number of channels is 2 per polarization (making 4 channels of 500 MHz each per antenna), and each of these should be separately tunable within the front end bandwidth. The present state of the art in digitizers allows channels up to about 2 GHz wide (4 GHz sampling rate, several bits per sample), so sampling does not constrain the channelization. Considerations other than cost may be important. In the case of strong in-band interference, a large number of channels is favored so that bad channels can be rejected before digitization.

- **Spectral Resolution**

  If the IF channelization is such that two pairs are employed, a minimum of 512 channels in each of the four 500 MHz IF channels is specified. The bandwidth of each channel would be adjustable by factors of two over a wide range, allowing widely variable spectral resolution. The spectral resolution should, at least, be comparable to that of the Millimeter Array, of order 0.05 km s^{-1} at high frequencies. This represents a factor of three improvement in the spectral resolution on the widest bandwidth now available, and an order of magnitude improvement in the largest spectrometer bandwidth now available.

  For bistatic planetary radar resolutions of $\sim$ 5 Hz are desired over a few kHz of bandwidth. This can be achieved by bandlimiting the input channels with filters and then drastically reducing the correlator clock rate, but might be better done by recording the digitized signals on tape and correlating in software off-line.

- **Output Time Resolution**

  Support of very short dump periods (<0.1 sec) is feasible for the correlator proper, but we know of no way to handle the data flow if all channels and baselines are used. We assume that each spectral channel of each baseline will have two integrating bins (say, noise calibration on/off or pulsar on/off) available to it; perhaps four bins could be provided, but not a large number. Observations requiring high time resolution (tens of msec) will have to make large sacrifices in other parameters, *e.g.*, spectral channels or baselines.

- **Fringe Rotation and Phase Switching**

  We see no reason to change the present VLA design in which fringe rotation is done in an LO at each antenna. (Moving it to after the digitizers implies a large increase in correlator size.) To accommodate the addition of nearby VLBA antennas, which do not have fringe rotation, there is a consensus that this capability should be added in an LO that is part of a "VLBA to VLA interface box." Similarly, the VLA phase switching scheme should be retained and that feature should be added to the VLBA antenna signals as part of the interface. It is noted that observations requiring high output dump rates might not be able to make effective use of the phase switching, thus limiting their dynamic range.

Careful consideration will be given to including hardware internal to the correlator for real-time detection and removal of short-time-scale interference. For example, it might be feasible (in an FX correlator) to examine each FFT for channels with excessive amplitude and delete those channels from the cross-correlation.

If possible, the development of a new VLA correlator should be combined with that of the Millimeter Array correlator. The overall similarity of the needs in terms of the antenna-bandwidth product should be exploited wherever possible. Unless the time scales on which the two correlators are required turn out to be significantly different, they should at least share the same basic architecture and the same ASIC(s).

5.4.1 Ultra-wide Bandwidth Performance

Current thinking regarding a new correlator and IF transmission scheme are based on a 2 GHz total bandwidth capacity (1 GHz in each of two polarizations). Since modern feeds can provide good performance over a bandwidth $\approx$35% of the center frequency in linear polarization, it is clear that a great deal of potential sensitivity is given up at the higher frequencies. An alternative is to consider an ultra-wide bandwidth system, in which accurate polarization, spectral resolution, and field of view are given up for maximizing the instantaneous bandwidth.

An ultra-wide-bandwidth correlator for continuum observations above 18 GHz could be built as a separate instrument from the main 1 GHz correlator. The required spatial field of view is likely to be a cost driver, since it determines the frequency resolution needed to avoid bandwidth smearing. Preliminary thinking indicates that 8 GHz/polarization at 200 MHz resolution might be feasible, but no cost estimates have been made. An analog correlator should be considered, especially if a coarser frequency resolution (>100 MHz) might be acceptable. Economic and performance tradeoffs should be studied for three approaches: a pure analog correlator, with optical fiber delay lines (considerable testing will be needed to see if adequate passband stability can be achieved); digital delay followed by conversion back to analog for correlation; and an expanded pure digital correlator. It is likely that the digital approach would win if frequency resolution <100 MHz is required.

It should be recognized that this is an expensive item that will be useful only at the highest frequencies, and that various compromises will prevent it from achieving very high dynamic range. Assuming a 35% bandwidth, and the improvements mentioned elsewhere in system temperature and antenna surface accuracy, sensitivities of better than 1 μJy in 12 hrs are possible between 18 and 40 GHz.

5.5 THE E CONFIGURATION

Support of an ultra-compact E configuration requires construction of new antenna stations and rail access to them. Careful consideration must be given to the number of new stations needed and their placement.

One possibility (E1) is to move the outer three antennas from each of the three arms of the D configuration to the inner part of the configuration. This option would require only 9 new stations and two new rail spurs (Fig. 5.4). The E1 configuration would have a maximum baseline of 500 m. Simulations have shown that it would achieve a given surface brightness sensitivity in half the time as an optimally tapered observation with the D configuration.

A more optimal configuration (E2) would require essentially 27 new stations and 5 or 6 new rail spurs. It could be designed to provide essentially Nyquist-sampled u-v coverage and a small grating response. Simulations of one such configuration (Fig. 5.5) indicate that it could be 5–10 times faster than the D configuration in reaching a given surface brightness.

A comparison of the relative sensitivities of the D, E1, and E2 configurations (parameterized as the filling factor of antennas in the area covered by the array) is shown in Fig. 5.6. While the E2

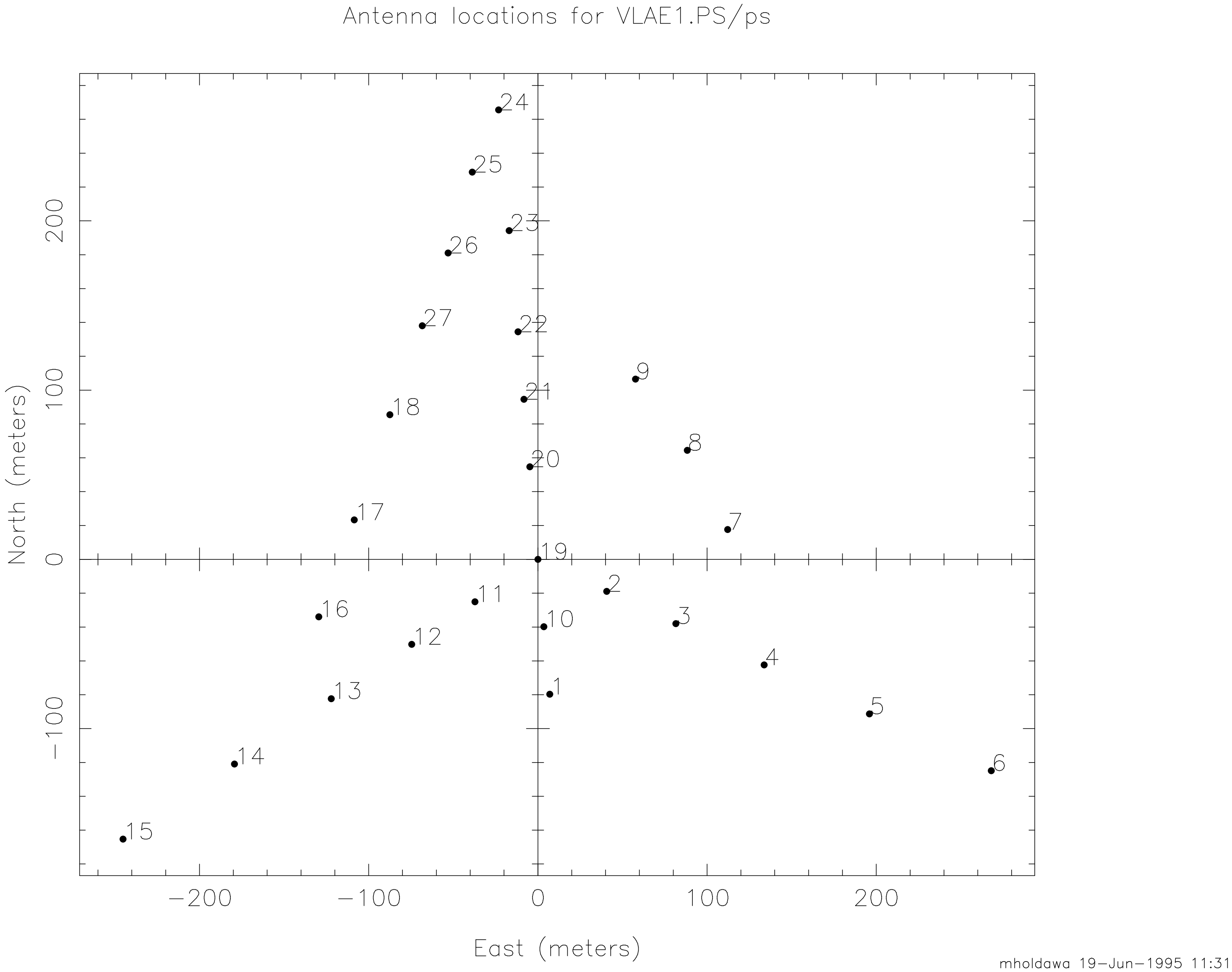


Figure 5.4: Example of a possible E configuration requiring only 9 new antenna stations and two new rail spurs.

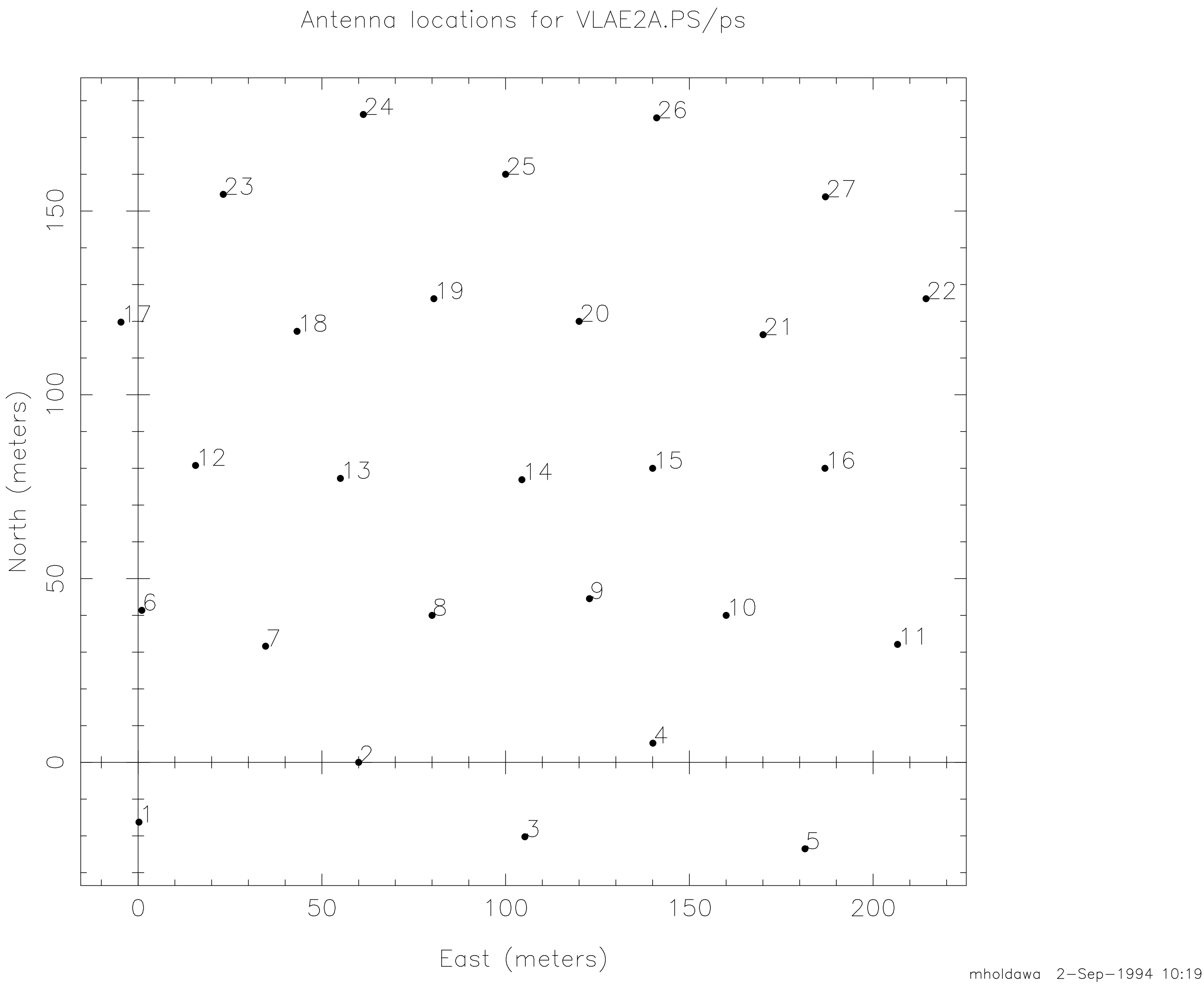


Figure 5.5: Example of a more optimum E configuration, requiring 27 new stations and 5 or six new rail spurs.

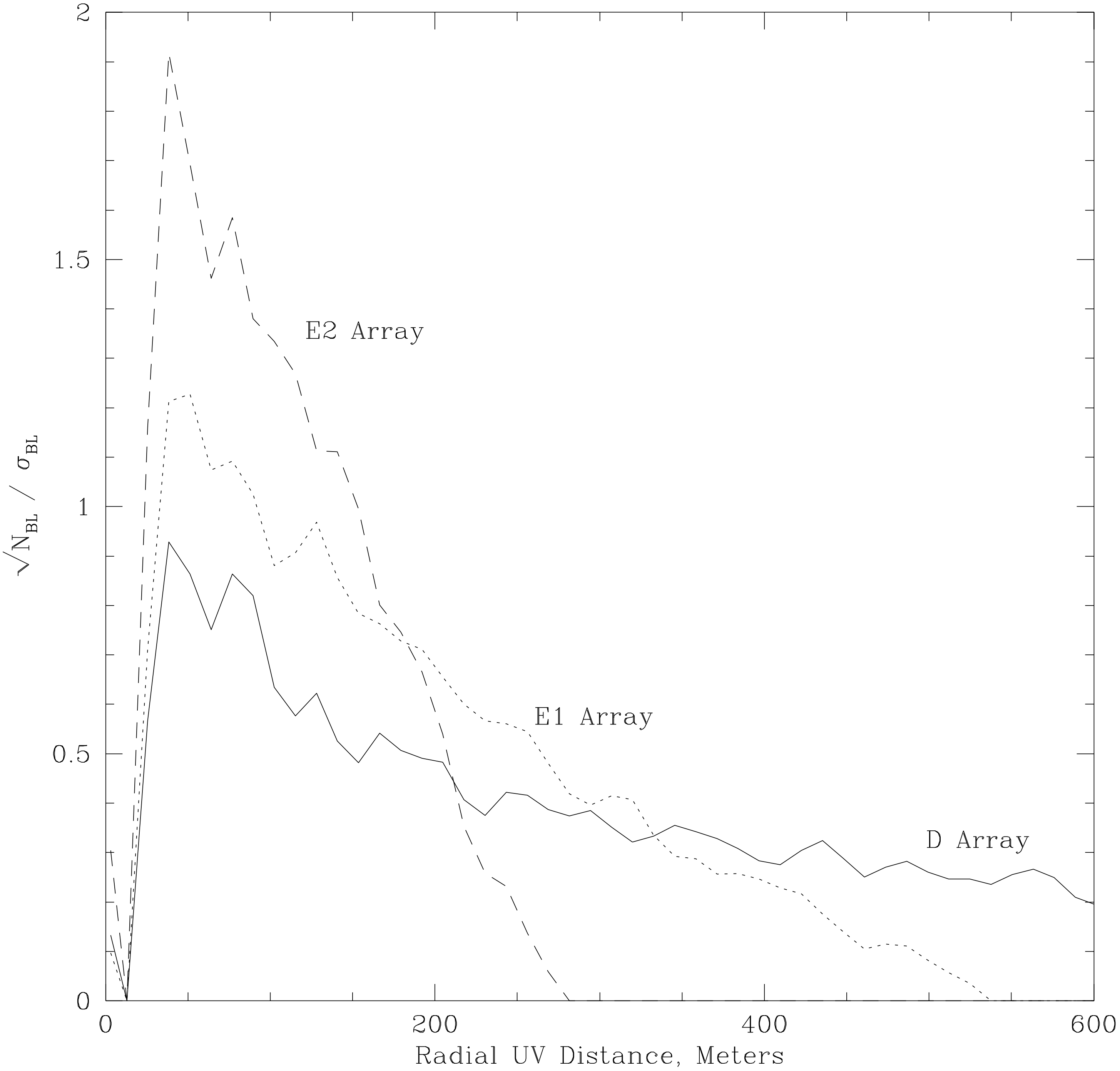


Figure 5.6: Relative sensitivities of the D, E1 and E2 configurations.

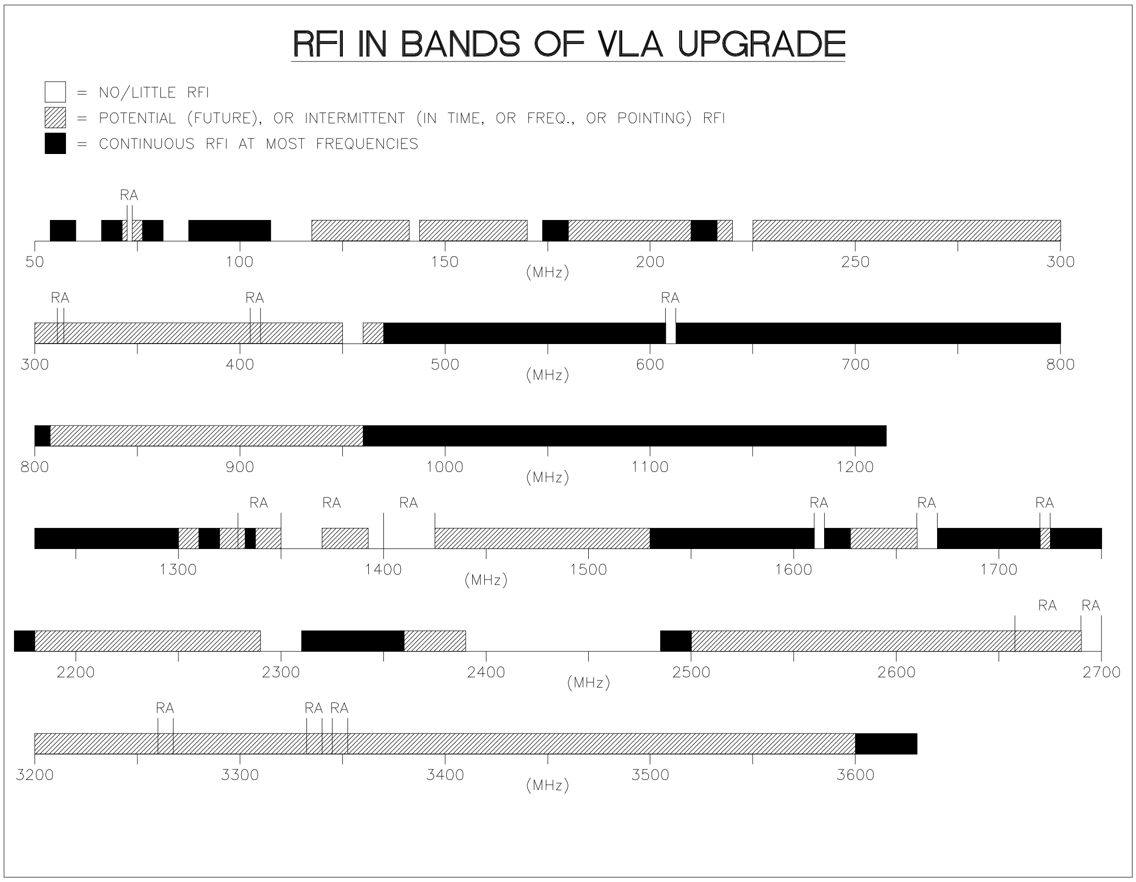


Figure 5.7: Potential for RFI in the Enhanced VLA Bands

configuration is preferable to the E1, preliminary cost estimates show that it comes at four times the cost of the E1. A detailed cost-benefit analysis is clearly needed.

Shadowing is of little concern for either of these possibilities. Simulations have shown that there is little shadowing for hour angles -3h<HA<+3h for source declinations $\delta \geq -10°$. Long tracks will not be needed for good u-v coverage; snapshots at several hour angles will suffice for many programs. For low declination sources, a hybrid or "E-south" array configuration may be needed.

The E configuration will be, above all, a mosaicing configuration. Successful exploitation of the E configuration will require a total power capability on all antennas, as discussed in §5.2.4.

5.6 RADIO FREQUENCY INTERFERENCE

An important consideration for the VLA Development Plan is the reality of radio frequency interference (RFI). The desire to upgrade the VLA to wide-bandwidth performance (of order 1 GHz per polarization channel) means that the instrument will often operate outside of the protected frequency bands. The array will therefore be susceptible to RFI to a even higher degree than it is now, especially at frequencies below a few GHz. It is unfortunately safe to assume that the RFI environment will be significantly worse when the VLA Development Plan is completed than

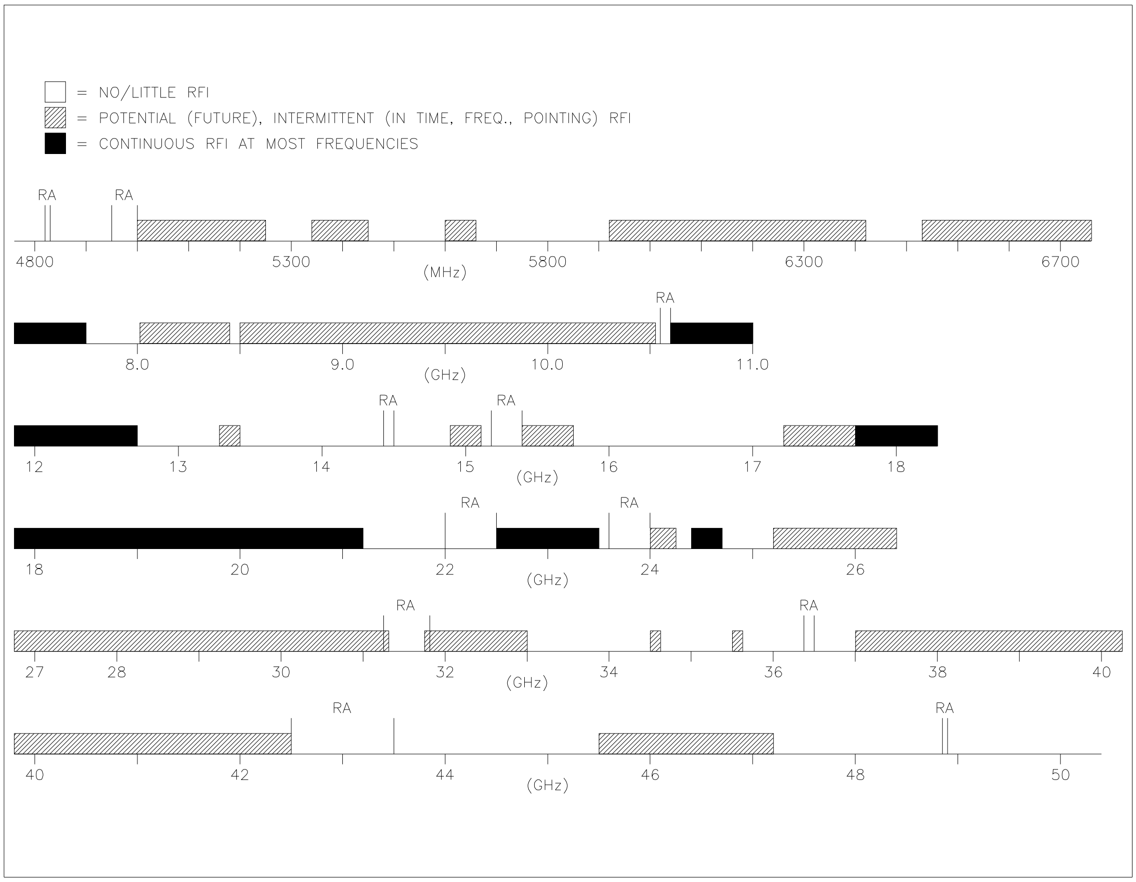


Figure 5.8: Potential for RFI in the Enhanced VLA Bands

it is now.. This results from the accelerating demand for mobile personal communications systems and from the fact that several areas of spectrum, previously lightly used and under the control of the Federal Government, are being transferred to the control of the FCC. It is essential that all equipment be designed with requirements for detection, rejection and excision of RFI in mind.

Some general statements, based on frequency allocation tables and preliminary RFI monitoring at the VLA site, can be made about likely RFI in the proposed enhanced VLA bands. Figs. 5.7 and 5.8 show the expected RFI problems for each band. Between $\sim 100 - 800$ MHz it seems unlikely that the wide-band low-noise amplifiers in a receiver covering this frequency range will be driven into compression by RFI. It will be essential, however, to provide filtering after the first 20-30 dB gain low-noise amplifier to prevent compression further downstream in the receiver electronics chain. This filtering should take the form of either a tunable bandpass filter or a number of switchable bandpass filters which pass only those frequency ranges needed for the observation and known to be relatively free of RFI. The selection of the filters and observing frequency range would be made on the basis of data provided by an RFI monitoring system to be located at the VLA site. Between 800–1200 MHz, the same remarks apply. The frequency range 840–920 MHz may become particularly difficult to use because of the proliferation of cellular telephones (except possibly for a short period late at night). The frequency range 960–1220 MHz will be problematic due to its allocation to aeronautical navigation uses. Between 1200–1750 MHz, it is unclear whether or not the filtering scheme proposed for the lower bands will be needed, but the possibility of installing it in the future should certainly be included in the design. There will almost certainly be unusable frequency ranges such as 1610–1627 MHz which is assigned to the mobile satellite service for which constellations of satellites totaling hundreds of elements in orbit are proposed. For the bands $\gtrsim 2$ GHz there should be fewer cases in which severe filtering will be required to prevent compression of the electronics. A frequency range where it is likely that filtering will be required is the Direct Broadcast TV Satellite Band 12.2–12.7 GHz. Any frequency range in any band assigned to a satellite down link or aeronautical application may become unusable.

While the use of independently tunable IF channels will allow users to "steer around" some of the more damaging sources of interference (*e.g.*, airport radar, GPS signals, etc.), it is impossible to avoid all sources of RFI. It is therefore highly likely that all observing will be done in spectral line mode, at least at low frequencies, to allow the identification and excision of RFI from the data in both the temporal and spectral domains. To do so will require increased spectral resolution and more sophisticated data flagging schemes in the early stages of post-processing. For example, various monitor data will be used, not only to identify system components operating in a non-optimal way, but to identify discrete times and channels corrupted by external RFI. These monitor data could be used by a first-stage offline system to flag and/or excise corrupted data before forming a pseudo-continuum data base for further processing.

In anticipation of a worsening RFI environment, we must actively monitor for RFI at the VLA site in all susceptible bands that are under consideration for the enhanced VLA. We must also begin research and development on the technology needed to solve RFI problems and to assess their seriousness for actual experimental situations. Examples of useful technology include: high dynamic range amplifiers and mixers, high performance continuously tunable bandpass filters and superconducting or cryogenically cooled filters. In parallel, a continuing development program is needed for software designed to assist in the automatic identification and excision of data contaminated by RFI. Finally, the actual impact of non-saturating RFI on observations that can use fringe rate and delay discrimination should be tested in the field. This may require building prototype systems on three antennas that could be used to sample the RFI environment on baselines that would be used in experiments such as the proposed high-redshift H I surveys.

5.7 SOFTWARE AND COMPUTING NEEDS

To make sensitive continuum images over wide fields of view at high resolution we need mosaicing and multi-frequency synthesis software which can handle large numbers of channels and make continuum and polarization maps over the entire primary beam. We must be able to look at the data; some sort of automatic flagging, preferably fairly flexible, is probably also essential. We must be able to find and reasonably analyze point sources in the midst of diffuse backgrounds at many frequencies; we must be able to do multi-resolution CLEANs or the equivalent routinely. We must reach dynamic ranges of 10^5:1 routinely, and several million to one with some effort. The latter target requires a concerted study of the problems which limit us now.

Real-time imaging is important for rapid imaging of variable sources to make good use of the new high-sensitivity systems.

Improvements in computing should accompany the enhancement of the VLA, as projects of all types will benefit. These should include streamlined procedures for combining data from the E configuration with data from the larger VLA configurations, autocorrelations, and single dishes. Techniques going beyond the current robust weighting and multi-resolution CLEAN may be needed to image structures on all available scales. Astrometry software for using VLA images fully in multi-wavelength high-resolution studies will also be important.

With more spectral-line channels, data sets will be larger, requiring files larger than the current

2 Gbyte limit and very large disks, perhaps with the ability to write extra-large files across disks. True joint-deconvolution mosaicing will be in demand. Both will bring about demand for faster processing.

Visualization and display of data sets with many channels will require more sophisticated displays and high-bandwidth transfer from recording media to such displays.

Finally, the on-line computing system must be upgraded to handle the additional antennas in Phase 2 of this plan.

5.8 COST AND SCHEDULE

The time scale for carrying out the VLA Development Plan is uncertain, as many engineering aspects of the plan have yet to be defined. The amount of work that will be contracted out and the amount that will be done by NRAO staff are also not yet decided. A fundamental requirement is that the VLA should continue to function as a user instrument while the enhancements are introduced. The impact of this on cost and schedule is presently uncertain, and requires detailed study. Nonetheless, some estimates can be made.

The time scale for the work on the Plains of San Augustin (Phase 1) will probably be set by the need to move antennas through the Antenna Assembly Building for overhaul. The tasks will include:

- New feed cone and receiver installation
- Normal preventive maintenance and retrofits
- Azimuth bearing replacements ($\sim$1 out of every 5 antennas)
- Possible quadrupod and FRM modifications

Allowing 4 antennas to have an 8 week overhaul and one antenna to have a 12 week overhaul (for the azimuth bearing replacement), the work on five antennas can be completed per year. This will be a tight schedule and will probably involve working two shifts per day. With 28 antennas, and adding a few months for startup and cleanup, the upgrade project will take 6 years. During that time there will often be two antennas out of the observing array for retrofits.

Six new cryogenic systems (including finishing 45 GHz) will be added to the array; a total of 170 cryogenic receivers will need to be built. Even if design and prototyping can be done before the main project begins, we still need to fabricate about 30 cryogenic receivers per year. During our normal receiver retrofit program we have built between 9 and 12 receivers per year. About 800 new LO/IF modules will have to be built.

Six years should be adequate time to complete the fiber optics system, the new correlator, and E configuration stations. At least two years of design and prototyping should precede the actual project start. If 1996 and 1997 are devoted to R&D, the parts of the upgrade that will be located on the Plains of San Augustin could be completed in 2003. As the normal VLA and VLBA maintenance and upkeep must be kept going throughout Phase 1, we will need to add about 30 people to the Engineering Services and Electronics Divisions for its six-year duration.

Table 5.1 gives an illustrative budget for all items in the VLA Development Plan.

Computing costs, other than for on-site control of the new antennas and the new correlator, are not explicitly included in this budget. They change more rapidly than other items (fortunately tending to decrease) with time. They will therefore be estimated closer to the time of requesting funds.

Table 5.1: Illustrative Budget

Item	Cost ($M)	Sub-Total ($M)
Phase 1		
Antenna LO/IF	5.5	
Antenna Mechanical	2.3	
LO/IF Transmission	2.5	
Central LO/IF	2.5	
Correlator	7.5	
Test Equipment	0.2	
Cassegrain		
1.20–1.75 GHz	0.8	
2.13–2.70 GHz	1.6	
4.80–6.70 GHz	1.4	
12.0–18.0 GHz	1.5	
18.0–26.5 GHz	1.5	
26.5–40.0 GHz	2.2	
40.0–50.0 GHz	1.5	
NRE	0.5	
Prime Focus		
75—300 MHz	0.8	
300—800 MHz	1.2	
800—1200 MHz	3.5*	
Sub-Total		37
E Configuration		
18 stations	4	4
Sub-Total Phase 1		41
Contingency Phase 1		6
Phase 1 Total		47
Phase 2		
4 new antennas	25	
Fiber to DS, PT	2*	
Fiber to BN,HL,VN,LA	8*	
Sub-Total Phase 2		35
Contingency Phase 2		6
Phase 2 Total		41
Plan Total		88
* cost is very uncertain		