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 HII Regions

Extragalactic HII 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 HII 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 HII regions out to Virgo. One should pick up many more of the optically-detected HII 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 HII 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 HII 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) HII 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 HII regions in nearby galaxies, and even resolve compact HII 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 $\sim$ 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 ($\geq$ 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 HI 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 HI 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 HI over the whole sky, simultaneously covering a redshift from 0 to 0.1. This will give a *complete inventory of HI masses irrespective of a stellar association* to 10^5 $M_\odot$ within the local group, to 2.6×10^7 $M_\odot$ at the distance of Virgo Cluster, 2.4×10^8 $M_\odot$ in Coma, to 3.5×10^{10} $M_\odot$ at the survey limit at a distance of 280h^{-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, 6.5×10^7h^{-3}Mpc^3 , is such that about 10^6 galaxies should be detected with HI 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 7×10^8 $M_\odot$ of HI 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}). HI masses of 4×10^9 $M_\odot$ will be detectable at the survey limit of $z = 0.2$, implying that normal galaxies with modest HI content can easily be detected. Note that currently the highest redshift at which HI 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 3×10^{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

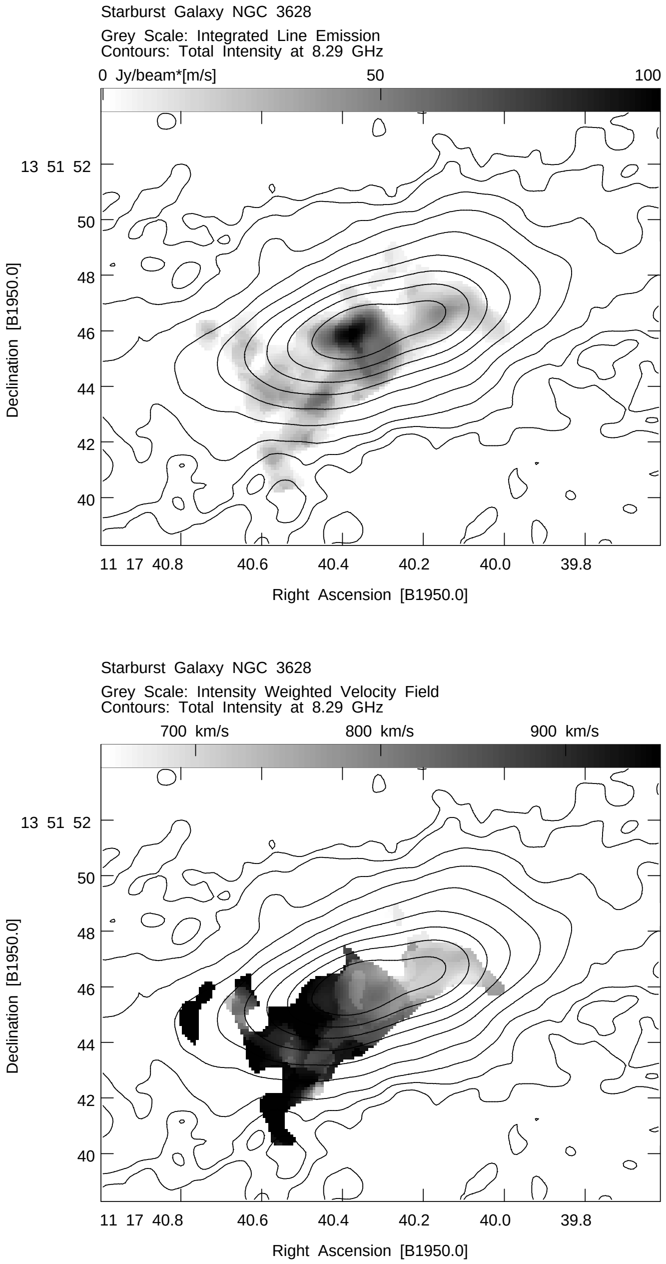

Figure 4.1: H92α images of the nuclear region in NGC 3628 made from the VLA observations by combining C and B configuration data; the angular resolution is $1.8'' \times 1.5''$. *(upper)* integrated H92α line emission (grey scale) and continuum emission at λ3.5cm (contours). *(lower)* the intensity-weighted 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 (~ 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 $\lambda 1.35$cm) 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 ~ 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($1\rightarrow0$) 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 ~ 0.03K for the CS($3\rightarrow2$) 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($1\rightarrow0$) 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($2\rightarrow1$) 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$4 line, which falls at 45 GHz. The peak main beam temperatures is ~ 0.085K for the HC_3N J=9$\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 $10(T_{\rm dust}/50$ 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 ab