Chapter 3

THE MILKY WAY GALAXY

3.1 INTRODUCTION

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

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

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

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

3.2 STAR FORMATION

3.2.1 Gravitational Infall

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

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

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

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

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

3.2.2 Proto-stellar Disks

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

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

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

3.2.3 Proto-planetary disks

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

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

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

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

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

3.3 MASSIVE STAR FORMING REGIONS

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

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

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

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

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

3.4 PMS AND MS STARS

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

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

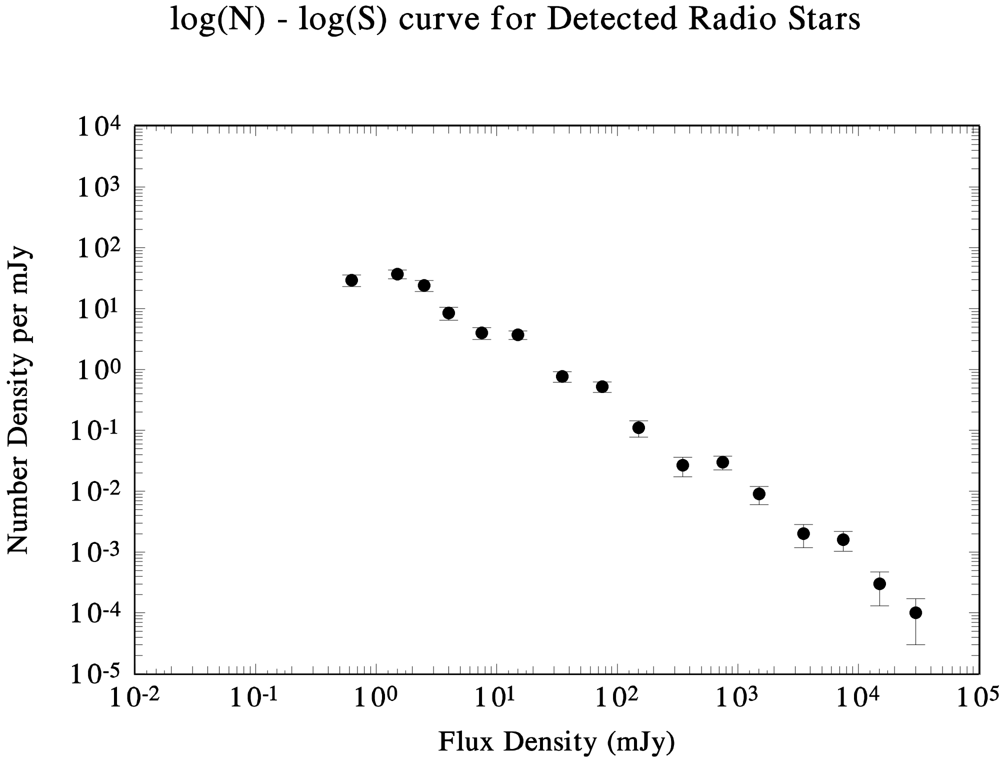

Figure 3.1: The log$N$–log$S$ curve for radio-detected stars.

require improved sensitivity for a proper radio census are:

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

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

- Cataclysmic variables: A very small number of these stars have been detected by the VLA,

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

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

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

3.5 ACTIVE STARS

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

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

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

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

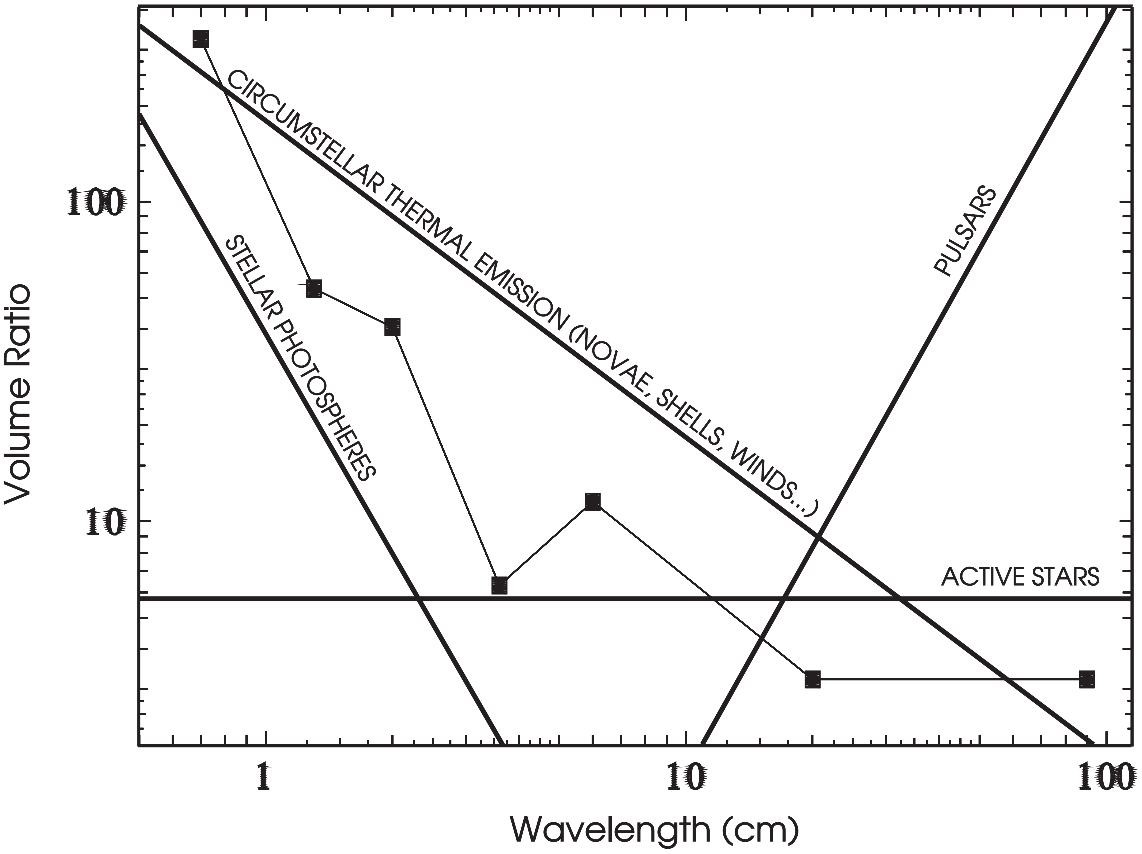

Figure 3.2: The line connecting squares shows the fractional increase in volume, as a function of wavelength, over which a radio source at a given luminosity would be detected by the upgrade in sensitivity. Characteristic radio spectra are shown for four categories of stellar radio sources.

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

3.6 STELLAR ASTROMETRY

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

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

3.7 IMAGING THERMAL EMISSION

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

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

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

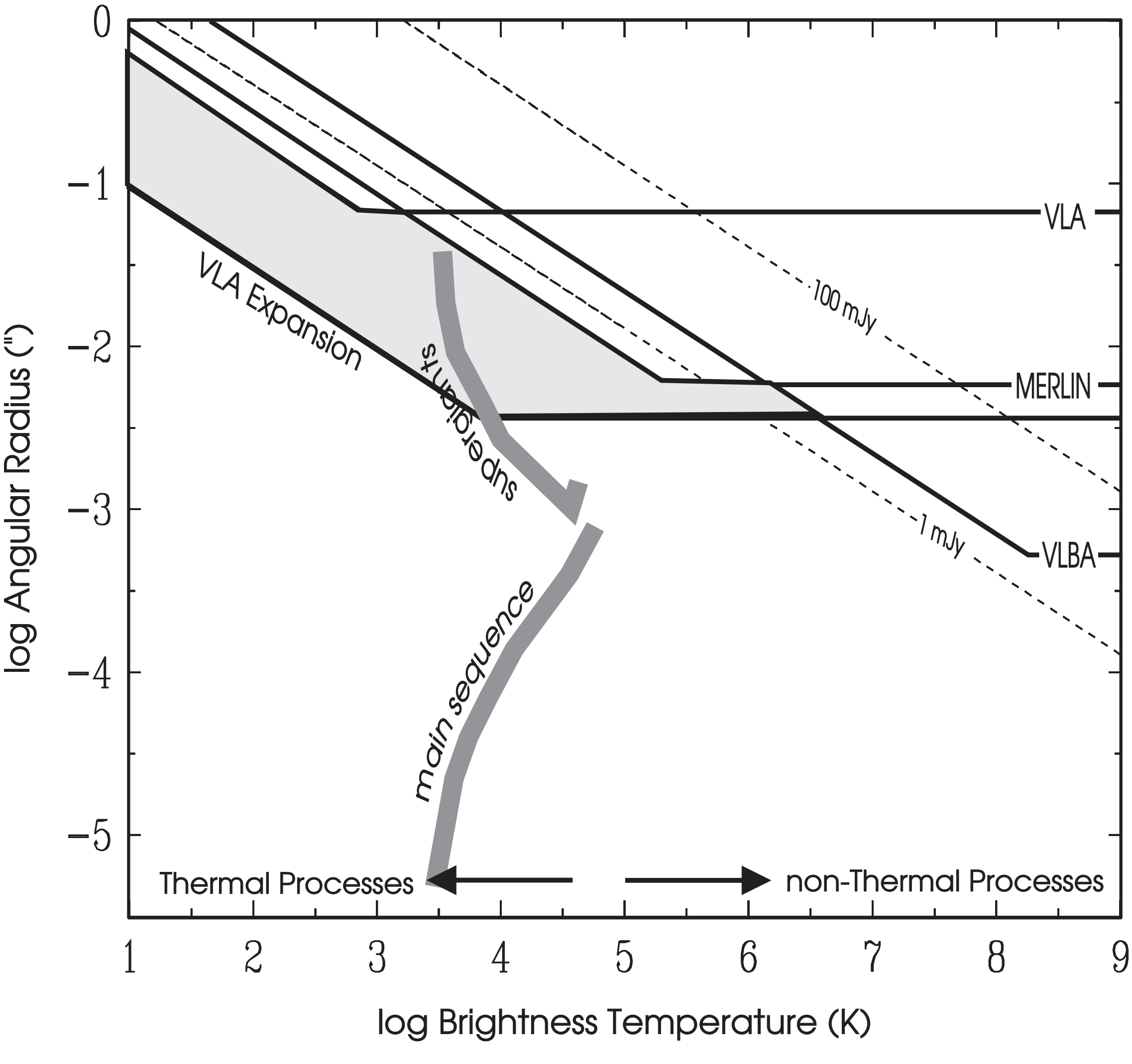

Figure 3.3: Brightness temperature and angular size regimes accessible to imaging by interferometer arrays. The previously inaccessible region that will be opened up by an expanded VLA with the upgrade in sensitivity is shown by the shaded area.

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

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

3.8 CIRCUMSTELLAR MASERS

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

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

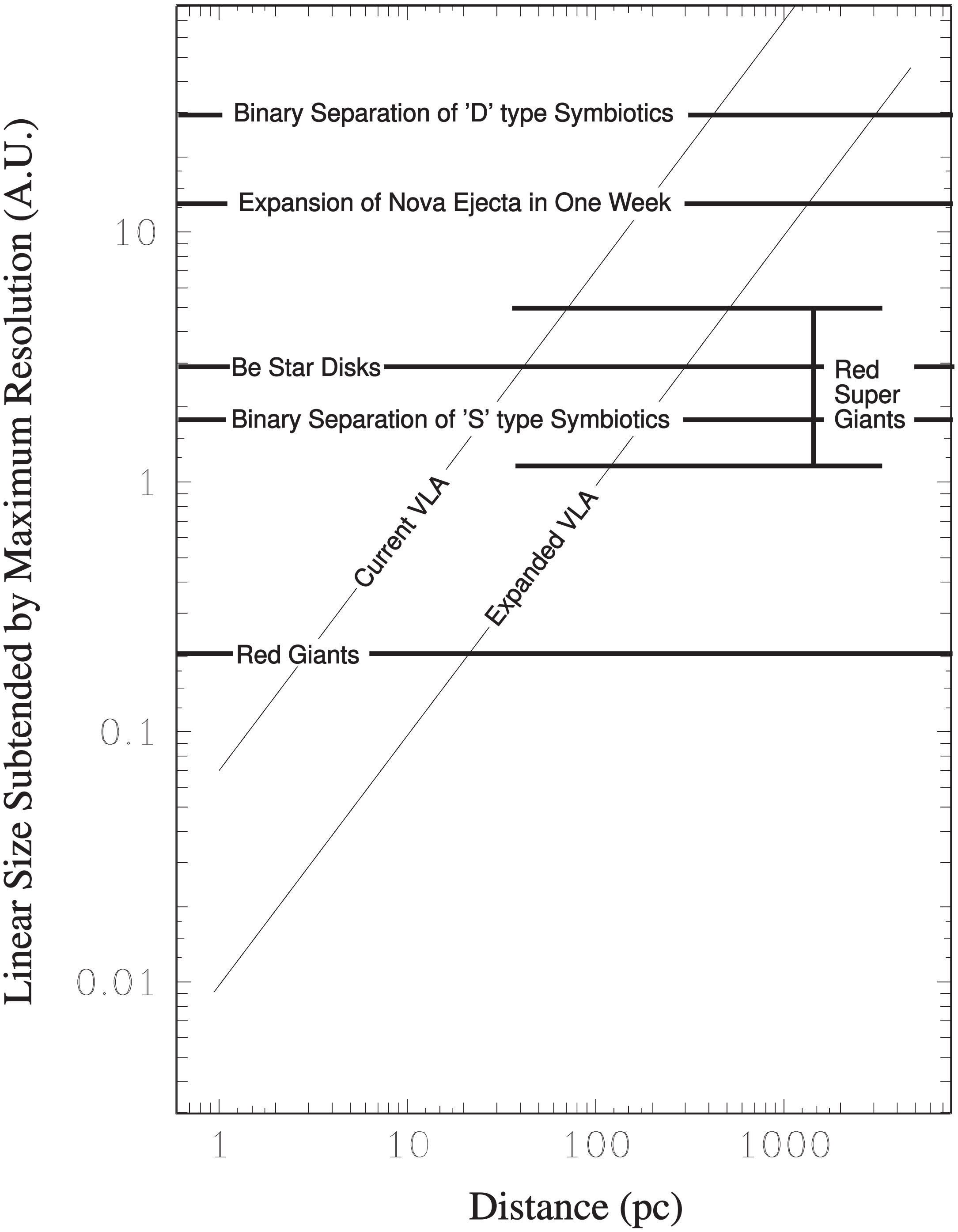

Figure 3.4: The resolving power of the current and A+ configuration compared to the linear dimensions of several known, thermal radio emitting astrophysical phenomena.

shells.

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

3.9 RADIO RECOMBINATION LINES

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

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

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

3.10 MOLECULAR LINES

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

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

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

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

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

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

Formaldehyde has been a staple molecule for centimeter-wavelength telescopes for many years. Unfortunately, only two lines have been available for study—at λ6cm and at λ2cm. These lines are affected by the well known excitation anomaly which causes them to be seen in absorption against the 2.7K background over much of a cloud's extent. Fortunately, the VLA will make available several very interesting new transitions with completion of the 45 GHz system. Formaldehyde may turn out to be the "molecule of choice" for probing physical conditions in clouds with the VLA. In addition to the λ6cm and λ2cm lines, the $3(1,2)\rightarrow3(1,3)$ line at 28.975 GHz, and the $4(1,3)\rightarrow4(1,4)$ line at 48.3 GHz could be available on the VLA. These lines are very useful densitometers. Mangum (1990) noted in his dissertation that these K-doublet transitions have a spatial density filter built into their excitation; for densities below 10^5 the formaldehyde lines are in absorption for J of 4 or below, while for densities above this value all are in emission. At $J \geq 5$, all lines will be in emission where the excitation is sufficiently robust. Mangum also showed that formaldehyde is less susceptible to abundance peculiarities than some other molecules, notably ammonia, which render interpretation of the observations difficult. Formaldehyde observations at higher frequencies will provide an excellent densitometer, free from the complex cloud-envelope effects which plague interpretation of lower-lying formaldehyde lines. Formaldehyde has been detected in several external galaxies; the additional higher frequency lines should be detectable in several galaxies with the VLA, providing valuable density information.

3.11 X-RAY TRANSIENTS

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

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

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

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

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

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

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

3.12 SUPERNOVA REMNANTS

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

3.12.1 Spectral Imaging

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

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

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

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

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

3.12.2 Integrated Spectrum Studies

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

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

3.13 PULSARS

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

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

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

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

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

3.14 LARGE-SCALE STRUCTURE

3.14.1 The Galactic Center

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

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

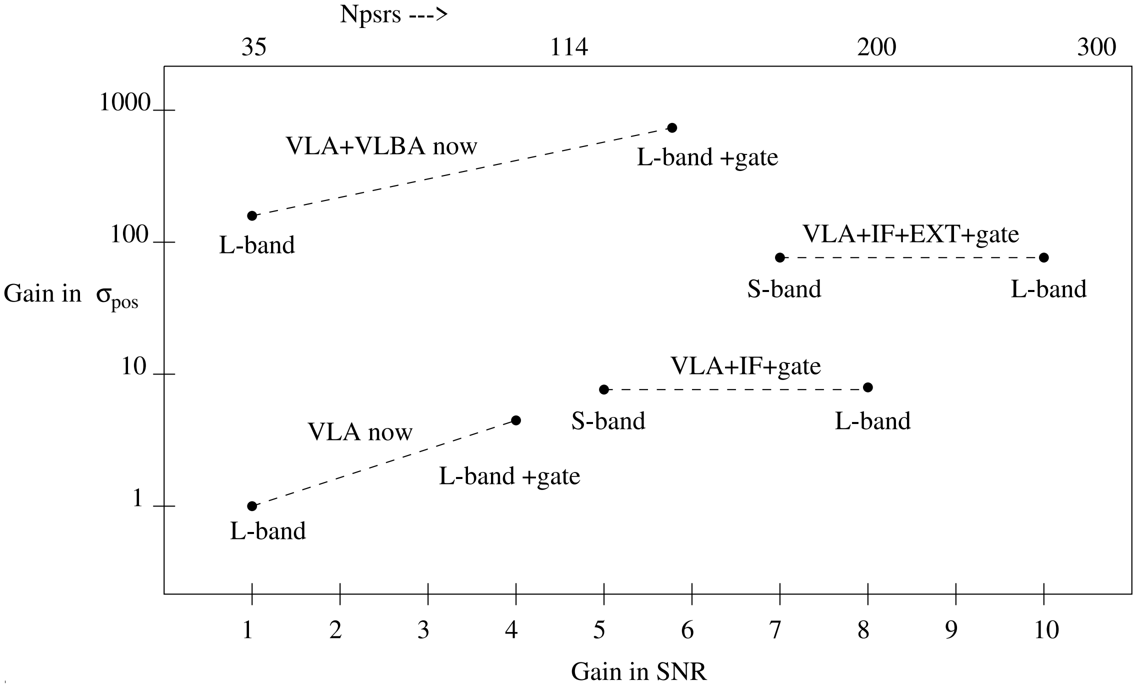

Figure 3.5: A comparison of the relative capabilities of several VLA configurations for pulsar astrometry. Shown are the current VLA and VLA+VLBA capabilities in the 1.4 GHz band, with and without the gate, as well the predicted capabilities of the enhanced VLA, with and without the A+ configuration.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

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

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

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

3.14.2 The Galactic Magnetic Field

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

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

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

3.14.3 Galactic Nonthermal Continuum Emission

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

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

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

3.14.4 Galactic H I

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

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

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

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