## 0.1 The VLA Expansion Project: Science with the A+ configuration

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The A+ configuration is the second phase of the VLA Expansion Project; its primary aim is to combine the excellent sensitivity of the expanded VLA with the superb resolution of the VLBA. This requires bridging the current gap in baseline coverage between $\sim$ 35 and $\sim$ 350 km, by providing fiber optic links between the inner VLBA antennas and the VLA, and by putting eight new 25m dishes at stations distributed at distances up to about 250km from the current VLA. The total cost is roughly $75M (including 20% contingency). These new antennas will effectively create three new instruments (Figures 0.1, 0.2):

- *The extended VLA:* VLA plus A+ plus inner VLBA
  At the high frequencies (10s of GHz), this combination will allow **milliarcsecond imaging of thermal objects.** The VLBA offers resolutions of a few milliarcseconds for sources brighter than $\sim 10^5$ K; the A+ configuration would lower this limit to a few hundred Kelvins. Synchrotron & coherent emission are strongest at low frequencies; the A+ configuration will give **0.1 arcsecond resolution for every source detected so far with the VLA**

- *The continental array:* VLA plus A+ plus full VLBA
  The gap in baseline coverage between the VLA and the VLBA causes severe problems in imaging structures of order 10s to 100s of milliarcseconds in size. The VLA cannot resolve such sources at frequencies below 10 GHz; the VLBA on the other hand resolves out most of the flux at all but the *lowest* frequencies, imaging the crests of the waves but missing entirely the ocean underneath. Consequently observers can make only poor images of many interesting sources (particularly those which cannot be detected over some range of frequencies), and detailed spectral index mapping is difficult or impossible. Combining the VLA, A+, and VLBA antennas will create **an array capable of high-quality imaging on scales from a few milliarcseconds to a quarter of a degree (at 1.5 GHz), and able to map sources with virtually identical uv-coverage from 0.3 to 45 GHz.**

- *A+ array alone:*
  With up to 8 GHz bandwidth in each polarization, the eight A+ configuration antennas *alone* will have roughly the same continuum sensitivity as the entire current VLA from 1–8 GHz, and up to 5–7 times *better* sensitivity above 10 GHz. The large bandwidth ratios will give reasonable uv-coverage through multi-frequency synthesis; the long baselines will give resolutions better than 50 mas above $\sim$ 10 GHz, while filtering out all structures larger than a few arcseconds. Hence, **the A+ array operating alone will be the perfect instrument for studies of transient events and surveys of compact sources.**

The remainder of this document details some of the science which will result from these new capabilities.

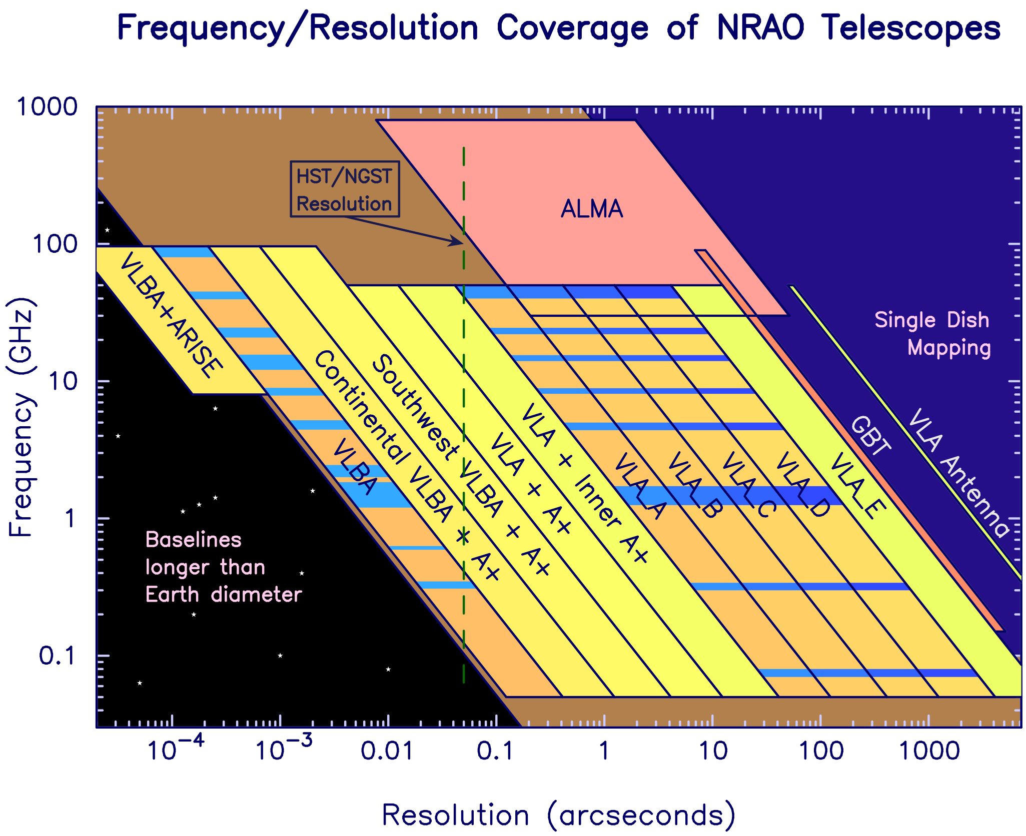


Figure 0.1: The frequency/resolution coverage of current and planned NRAO telescopes. The horizontal blue strips show the capabilities of the current VLA; the yellow shows the improvement after the VLA Expansion Project, with the areas specific to the A+ configuration indicated. Note that the new frequencies below 1 GHz rely on the prime focus system, for which the current proposal requests only development funds. It is not yet clear what the lowest frequency on the ALMA will be, though it will certainly be $\gtrsim 30\,\mathrm{GHz}$ (as shown in this figure).

### 0.1.1 Milliarcsecond Resolution of Thermal Emission

The A+ configuration will allow detailed imaging of sources as faint as a few hundred Kelvins, at resolutions as high as a few milliarcseconds (Figures 0.2, 0.3).[1] This opens up whole new classes of sources to detailed imaging:

- *Stellar atmospheres, binary stars, winds, and novae:*
  A few milliarcseconds corresponds to a few A.U. at 1 kpc. This distance is typical of a number of interesting phenomena:
  - giant and supergiant photospheres (cf. Betelgeuse)
  - interactions and ejections:
    - binary separations of semi-detached interacting binaries containing giant stars, such as symbiotic stars and recurrent novae
    - winds and circumstellar environments of early-type stars
    - the very early stages of novae outbursts: Apart from the best available mass estimates, sequences of radio images can show directly the *three-dimensional* distribution of both temperature and density within the source: the decreasing opacity effectively 'peels the onion,' allowing one to see deeper and deeper into the source.

    *The A+ configuration will finally allow imaging of thermal radio emission on the scale of the interaction that gives rise to the ejecta.*

  Fig. 0.6 shows the maximum distance to which these and other types of object would be resolved by both the A and the A+ configuration. The space density of these objects is so low that there are essentially no examples within the current A configuration limit; A+ configurationextends the resolvable distance to hundreds or thousands of parsecs, allowing us to image significant populations of all of these types of sources on AU and smaller scales for the first time.

- *Proto-planetary disks*
  Observations at a few 10s of GHz are required to see through the dust, into the centers of the dense inner (solar system) regions of proto-planetary disks. A+ configuration is required to do so with sufficient resolution to image such disks: present estimates suggest $\gtrsim 500$ such disks within 500 pc of the Sun, with total flux densities of order 160 $\mu$Jy at 45 GHz, and expected diameters of about 100 AU (200 mas at 500 pc). The A+ configuration could image these sources at 4–20 mas (2–10 AU) resolution, depending on their brightness distributions. Observations at several frequencies would trace different 'shells' of dust within the proto-planetary disk.

- *Galactic H II regions:*
  Hypercompact H II regions are a few hundred AU across; they must either be very young, or be confined by impressive dynamical or magnetic pressures. The A+ configuration will

[1] MERLIN is at least 50 times less sensitive than the A+ configuration. Furthermore, MERLIN's frequency coverage is restricted to 5 relatively narrow bands, and the limited number (28) and range (6.4–217 km) of baselines makes it almost impossible either to image complicated or extended sources, or to produce accurate spectral index maps. Combining the VLA and the A+ array by contrast gives almost 24 times the number of baselines, providing much denser coverage from 0.68 to 350 km, at *all* frequencies between 1 and 50 GHz. It is only a slight exaggeration to say that the A+ configuration is to MERLIN what the current VLA is to the prototype Green Bank Interferometer.

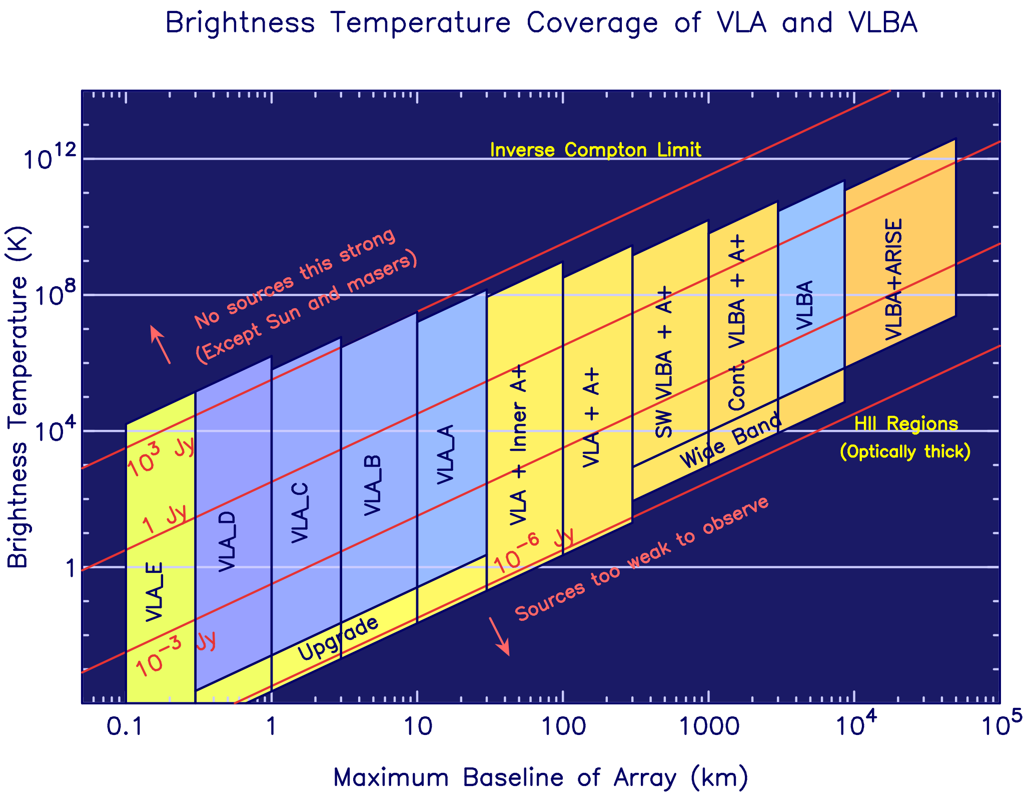


Figure 0.2: The brightness temperature sensitivity vs. baseline length for the VLA, VLBA, and ARISE. Current capability is shown in blue; improvements due to the VLA Expansion Project and ARISE are shown in yellow. The number of sources increases dramatically towards the lower right (lower flux densities).

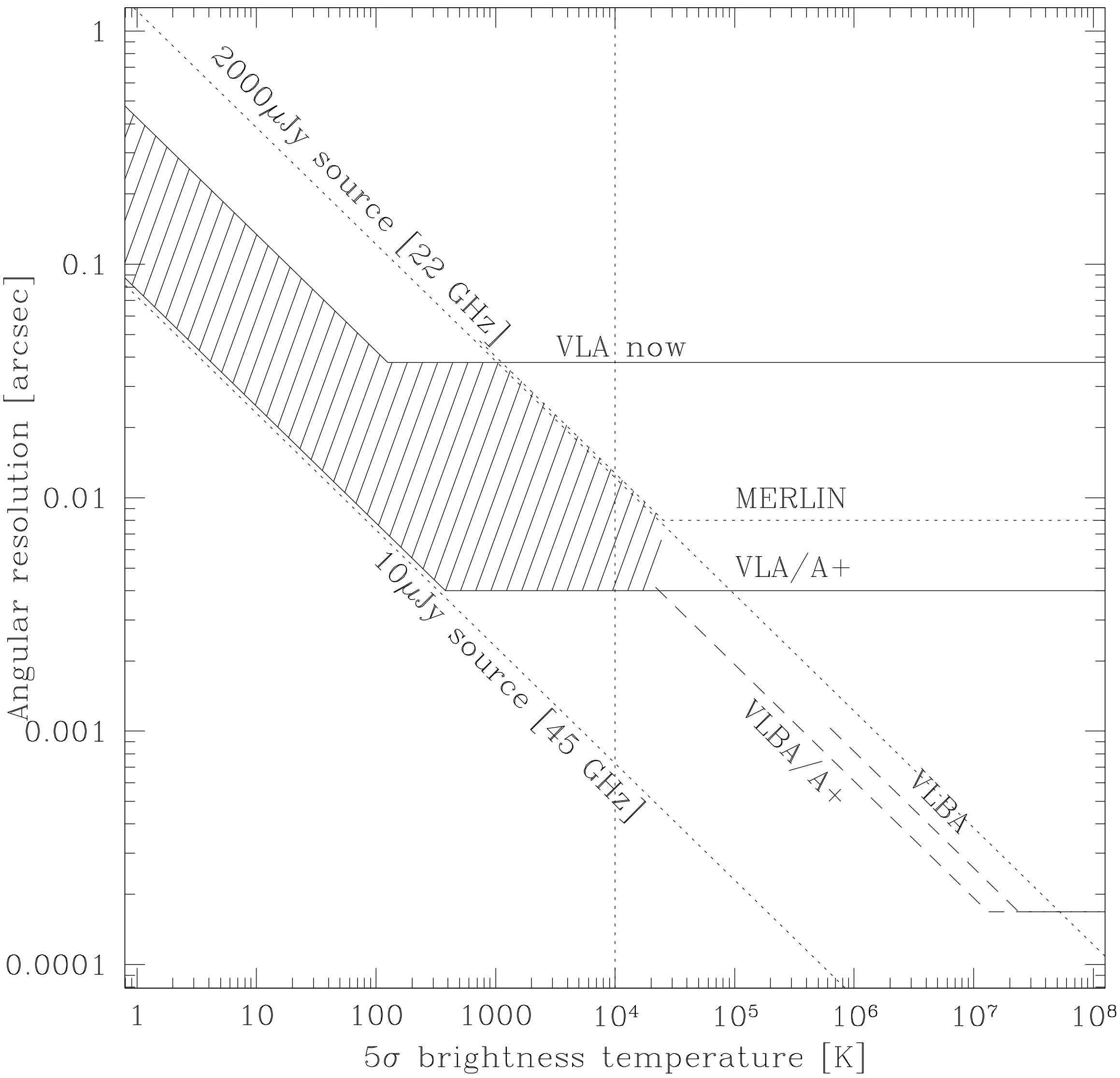


Figure 0.3: Brightness temperature and angular size regimes accessible to imaging by radio interferometers (12-hour integrations). The previously inaccessible region that will be opened up by the A+ configuration is shown by the shaded area. ALMA's best resolution will be $\sim 5\,$mas for 15km baselines at 850 GHz, with a $5\sigma$ detection limit of about $20\,\mu$Jy (for $64 \times 12\,$m antennas).

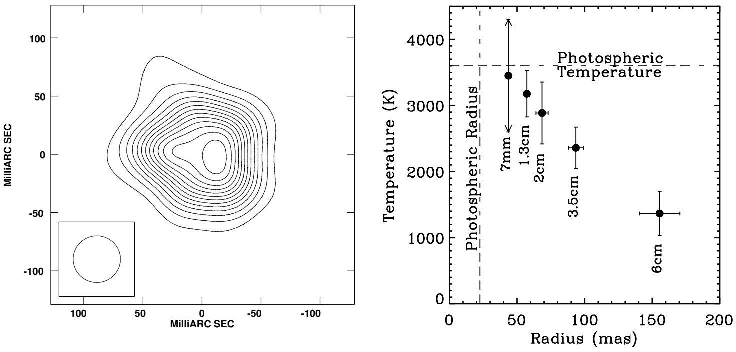


Figure 0.4: (*left*) VLA 43 GHz image of Betelgeuse. The resolution is 40 milliarcseconds and the contour interval is 250 K (brightness temperature). (*right*) The variation of temperature in the atmosphere with radius, determined from the VLA observations of Betelgeuse at different frequencies which resolve the source size (Lim *et al.* 1998). The A+ configuration will give a factor $\sim 9$ higher resolution at 30 times higher sensitivity.

resolve these regions for the first time (n.b. resolution is 30 AU at the Galactic center), and (through astrometric and morphological studies) show show directly whether or not they are freely expanding.

- *Extragalactic H II regions:*
  While MERLIN has been able to image individual supernova remnants in a few star-burst systems, no similar, systematic radio study of H II regions has yet been possible. The A+ configuration could detect and image *individual* compact H II regions (0.5pc, EM=$10^7$) as far away as M82 – a single 12-hour observation at 33 GHz would yield 0.1pc resolution images of every compact H II region within the 1.4 arcmin beam. Supernova remnants of course would come along for free, with sufficient resolution and sensitivity to make spectral index maps and search for polarization at the levels typical of Galactic remnants.

### 0.1.2 Microarcsecond Astrometry and Proper Motions

The VLA Expansion Project will provide a unique combination of sensitivity and angular resolution, making the VLA's A+ configuration the instrument of choice for astrometric observations of faint sources (see Table 0.1.2), allowing parallax measurements of 1 mJy sources to distances of several kpc in only a few hours. A few possible science projects are listed below.

#### Stellar Astrometry

- *Parallaxes of active stars to several kpc*
- *Planetary nebulae & stellar winds*
  It takes roughly 1 year to move 1 AU at speeds of 10s of km/sec. Hence, milli-arc-second resolution will allow direct measurement of the angular expansion rates of slowly expanding thermal objects such as compact planetary nebulae and wind interaction shells. Combined

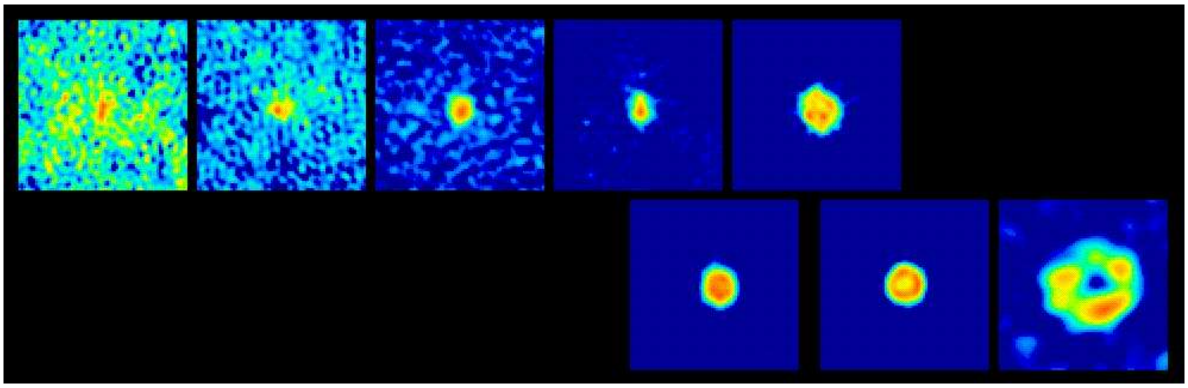

Figure 0.5: MERLIN (*upper*) and VLA (*lower*) images of Nova V1974 Cyg 1992 (Pavelin *et al.* 1993; Hjellming 1996a,b). The 5 GHz MERLIN data were taken 81, 106, 155, 173, and 271 days after outburst; the 22.5 GHz VLA data were taken 255, 313, and 769 days after outburst. Note the evolution from a centered-filled source highly elongated north-south, to a shell slightly elongated east-west. This corresponds to the change from optically thick to optically thin emission, with the later images 'peeling away' the outer skin to reveal the three-dimensional structure. The A+ configuration will have more than 30 times the sensitivity of MERLIN, and (by mapping at 45 GHz) about 10 times higher resolution. Novae like this one could be imaged within a few days of the explosion.

with spectroscopic data, such measurements can provide accurate distances out to several kpc.

- *Direct measurements of binary motions*
  Astrometric observations would directly measure 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.

- *Radio/optical frame tie*
  Combined with the observations of bright stars from the *Hipparcos* and *SIM* missions, 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.

### Jets in young and proto-stellar objects

Outflows are quite often associated with young and proto-stellar objects. Measuring changes in these jets over time – variations in flow rate and possibly direction – requires the A+ configuration, even for relatively bright jets. Moving knots have been detected a few hundred AU from the exciting star in the HH 80-81 jet (Martí, Rodríguez, & Reipurth 1998); this required multi-epoch observations, separated by several years, of one of the brightest outflows in the sky. Are these enhancements in the flow periodic? Are these variations the rule or the exception? The A+

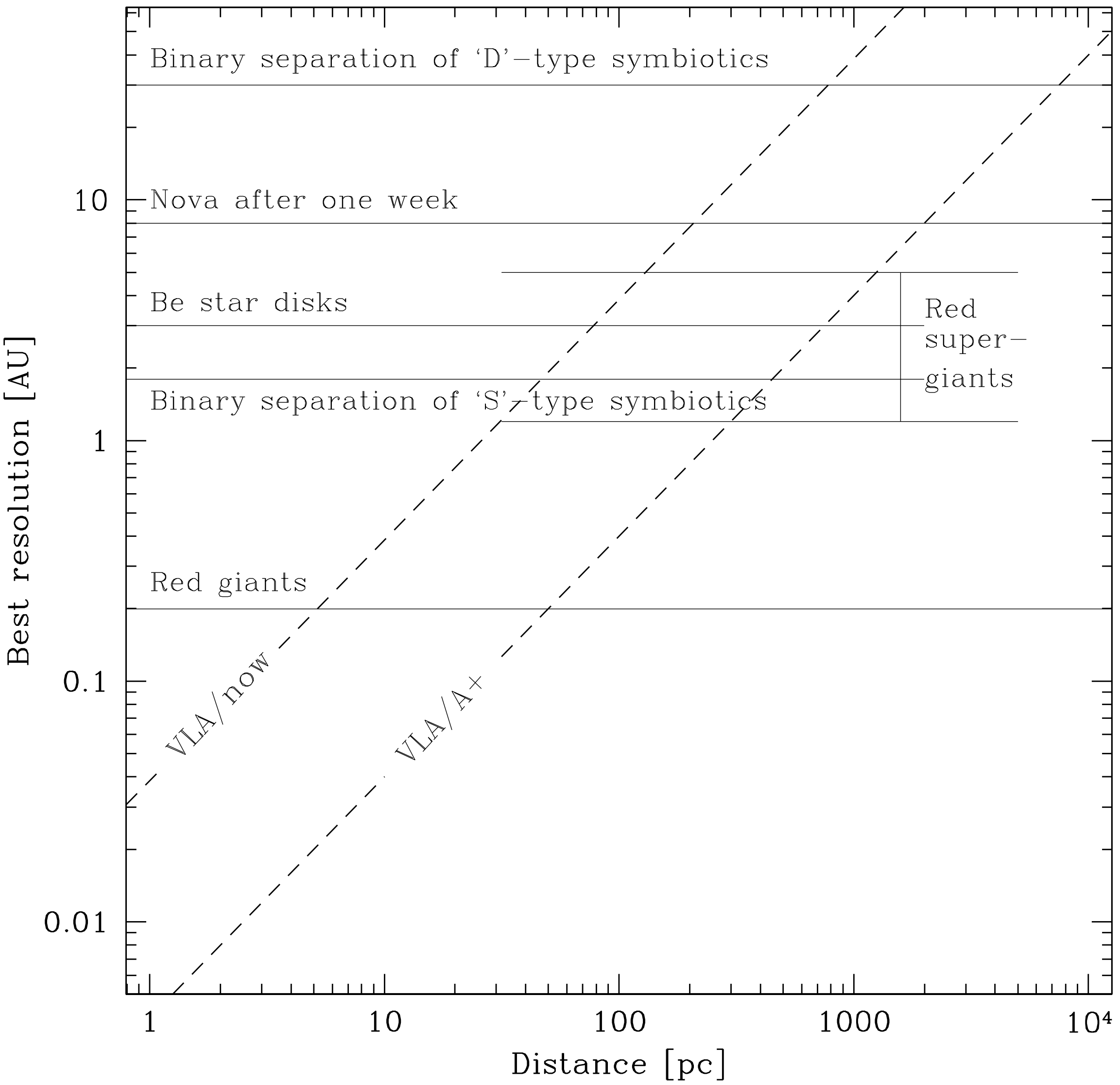


Figure 0.6: The resolving power of the A and the A+ configuration compared to the linear dimensions of several known, thermal, radio-emitting astrophysical phenomena.

**Table 0.1.2. Astrometry with the A+ configuration**

| Frequency (GHz) | Resolution (milliarcsec) | Rms Noise ($\mu$Jy) | Rms Position ($\mu$arcsec) |
|---|---|---|---|
| 0.25 | 800 | 88 | 70,000 |
| 0.37 | 500 | 42 | 21,000 |
| 0.57 | 340 | 20 | 6,700 |
| 0.90 | 220 | 8.1 | 1,800 |
| 1.50 | 125 | 4.4 | 550 |
| 3.0 | 64 | 2.7 | 170 |
| 6.0 | 32 | 1.8 | 59 |
| 10.0 | 20 | 2.2 | 44 |
| 15.0 | 13 | 2.2 | 29 |
| 22.0 | 9 | 2.7 | 24 |
| 33.0 | 6 | 2.4 | 15 |
| 45.0 | 4 | 5.6 | 23 |

Astrometric accuracy of the A+ configuration, defined as the resolution divided by the signal-to-noise ratio achieved for a 1 mJy point source in 2 hours.

configuration will provide the answers, detecting proper motions of 30 km/sec at kpc distances with only a month between the observations.

**Pulsars**

The A+ configuration will be the best instrument in the world for pulsar astrometry. Most such measurements today are done at 1.4 to 1.8 GHz because of the sharp decline in flux density with frequency ($-2.4 \lesssim \alpha \lesssim -1.4$, $S_\nu \propto \nu^\alpha$). With the expanded VLA, most pulsar astrometry will probably be done in either the 2–4 GHz band or the 4–8 GHz, since the increase in sensitivity more than compensates for the roughly 4 or 16-fold decrease in brightness. The higher frequency not only provides a smaller beam, but also reduces ionospheric effects by the square of the frequency ratio. Accurate parallaxes could be measured for $\sim$ 150 pulsars out to 3 kpc, and for $\sim$ 50 out to 8 kpc. In addition to providing a large number of distances independent of electron density models, these data will yield very sensitive proper motion estimates, giving an unparalleled data base of pulsar space motions.

**The Galactic Center**

The A+ configuration will allow measurements of ionized gas proper motions within a few tenths of a parsec of the Galactic center with accuracies of about 1 km/sec within a single year, making it possible to measure *accelerations* as well as simple velocities. Similar studies of stellar OH, $H_2O$, and SiO masers will provide even stronger constraints on the Galactic mass distribution on scales

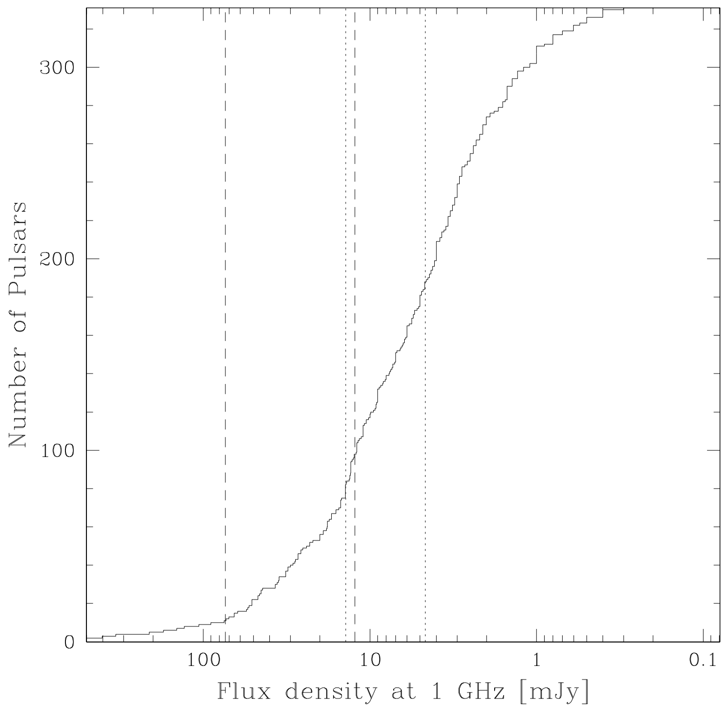


Figure 0.7: Cumulative distribution of pulsar flux densities. The vertical lines indicate flux density limits for two different parallax estimates: the dashed lines show pulsars whose distances could be measured to 8kpc, while the dotted lines show pulsars with distances out to 3kpc. The two lines in each case correspond to the range of measured spectral indices ($-1.4$ to $-2.4$).

out to hundreds of parsecs. A microarcsecond at the Galactic center corresponds to about a million kilometers; measurements of this accuracy will become straightforward with the A+ configuration, especially since Sgr A* itself provides an excellent positional reference.

### 0.1.3 Scattering

The A+ configuration will contribute unique and critical information on scattering (and hence turbulence). Here we concentrate on two specific examples: the solar wind, and the Galactic center.

#### Turbulence in the interplanetary medium

The solar wind inflates a cavity around the Sun, extending to perhaps $\sim$ 100 AU, called the heliosphere; this is filled with a tenuous, magnetized plasma, known as the interplanetary medium (IPM). Radio interferometers like the VLA are ideally suited for measuring the angular broadening and intensity scintillations of background sources viewed through the IPM; these data can be used to deduce the solar wind speed and acceleration profile, to measure properties of the turbulence, and to map large-scale structures in the solar wind.

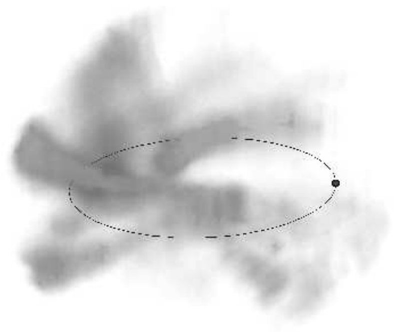

Figure 0.8: An example of a tomographic reconstruction of the inner heliosphere, to a distance of 1.5 AU, which was derived from a combination of IPS intensity level data and velocity data obtained over one solar rotation period (23 June 1994 to 20 July 1994, Carrington Rotation 1884). Earth's orbit is as indicated. The technique is described in detail by Jackson *et al.* (1998).

Extension of the VLA to baselines of hundreds of kilometers will open up a number of exciting possibilities. The A+ configuration will sample baselines covering more than two orders of magnitude in spatial scale. This not only expands the range of solar elongations that can be probed in a given frequency band, but will enable a critical portion of the spatial spectrum of the solar wind turbulence to be probed directly. The spatial spectrum of the solar wind is flatter than Kolmogorov on spatial scales less than some 10s to 100s of km, yet may be Kolmogorov-like on the largest spatial scales. The transition presumably occurs on spatial scales that will be sampled directly by the A+ configuration. Coupled with the VLBA, the A+ will provide comprehensive measurements of the spatial spectrum of the solar wind, as well as its temporal and spatial evolution, thereby providing powerful new constraints on the source, structure, and evolution of MHD turbulence.

Further, since the scattering measure falls off as $r^{-4}$, the A+ configuration configuration will allow the measurement of scattering properties over a much larger range of solar elongations.

#### Scattering sizes in the Galactic center

Scattering of radio waves by thermal electrons along the line-of-sight broadens the images of OH masers near the Galactic center, as well as Sgr A* itself. Typical scattering disks are in the range 0.1 to 1 arcsecond, too small to be resolve by the VLA's A configuration, but too large to be imaged with the VLBA. The A+ configuration would be perfect for these observations, which are interesting both for studies of the scattering medium, and for measurements of the magnetic field strength & direction through Zeeman splitting.

### 0.1.4 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 A+ configuration will contribute substantially to understanding of the dynamics and structure of these maser shells. 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 arcsec resolution of the VLA in the A configuration just barely resolves the shell structures but VLBI data resolve most of the larger scale structure. Polarization observations throughout the circumstellar shell are important because they can give significant information about magnetic fields and/or the maser process itself.

### 0.1.5 High-resolution Multi-frequency Observations

The gap in coverage between the VLBA and the VLA has particularly pernicious effects for sources a hundred or more milliarcseconds across, where the VLBA (even with a VLA antenna added) over-resolves them at all but the lowest frequencies (300–600 MHz), and the VLA only begins to pick them up at 45 GHz.

### Active Galactic Nuclei: Beyond Jets

VLBI in the past has given very detailed images of the relativistic jets ejected from massive central black holes, but has offered little information on either the accretion disks which feed those black holes, or their local surroundings. Recent VLBA observations have begun to hint at the potential of two powerful new techniques: high-sensitivity spectral index mapping, and high-resolution imaging at low frequencies. Both are currently limited by the lack of intermediate VLA/VLBA baselines to a few sources which happen to be just the right size; the A+ configuration is desperately needed to extend this work to a more typical and much larger sample.

- *Imaging extragalactic accretion disks on parsec scales*
  Figure 0.9 shows matched-resolution VLBA images of 3C84 from 5 to 43 GHz. Notice the complex spectral structure of the source – the southern extension which is seen only at low frequencies, the gradual elongation of the northern source towards the nucleus as the frequency increases, and more subtle effects within the individual lobes. This is incontrovertible proof of free-free absorption against the northern lobe; by mapping the spectral index across the source, the authors were able to derive the parameters of the obscuring disk, including size, scale-height, and rough density distribution. This sort of imaging simply could not be done before the VLBA came on-line, because changing frequencies was so difficult; but even now it can be done for only a handful of sources, those which happen to fit (at several frequencies) within the very limited spatial dynamic range of the VLBA, and which happen to have turnover frequencies in the correspondingly-limited spectral range. This is equivalent to making spectral index maps with only one VLA configuration. Those few sources which *have* been explored in this way show a variety of structures and scale-heights; the A+ configuration is crucial to extending these measurements to a wider variety of sources.

- *Milli-halos*
  This same source was discovered also to have a very small ($<$ 1 kpc) low-frequency halo (Silver, Taylor, & Vermeulen 1998; Figure 0.10), which is probably produced by particles diffusing out from the nucleus. The science interest here is the ability to track particles as they escape from the central engine – ideally one would make spectral index maps to track the spectral aging, and use shorter-baseline information to figure out how far this halo actually extends. At the moment this is impossible – the source was just barely visible to the VLBA with a single VLA antenna added, and only at the lowest frequency was it seen at all. The A+ configuration would make this sort of imaging much easier, and extend it both to a wider range of frequencies, and to larger halos.

- *A starburst in Mrk 231?* (Taylor, Silver, Ulvestad & Carilli 1999, in press)
  Another example of very interesting VLA/VLBA overlap science that is almost impossible now is the starburst in the central kpc of Markarian 231. Here the VLBA just barely picks up diffuse emission from the central kpc disk at 300 & 600 MHz, while the VLA has great difficulty resolving the disk even at 22 GHz. The disk seems to have a steep spectrum at high frequencies, characteristic of optically-thin synchrotron emission; the 1.4 GHz VLBA image resolves out most of the disk but leaves four point-like sources which may be supernova remnants. If one attributes the disk emission to star formation one requires a star formation rate of some 220 $M_\odot$/year. This is obviously interesting stuff, but the VLA/VLBA gap makes

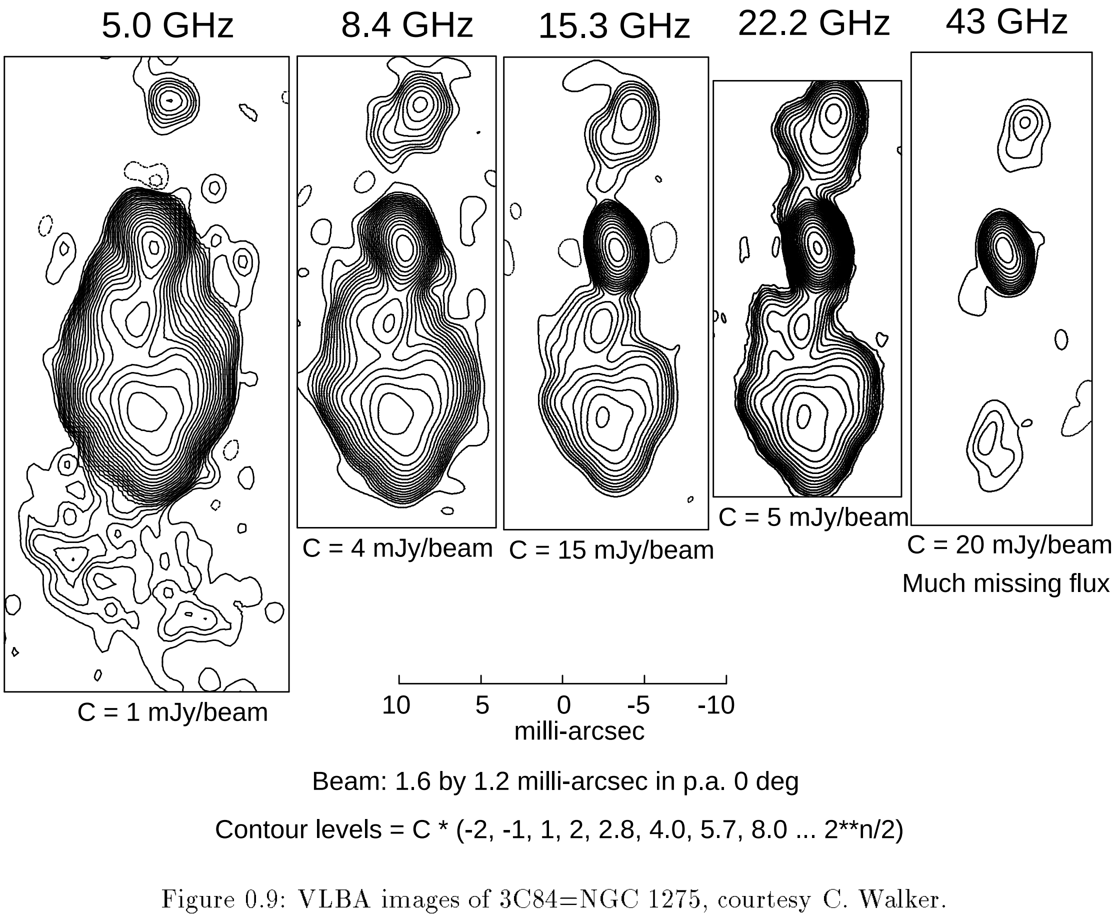


Figure 0.9: VLBA images of 3C84=NGC 1275, courtesy C. Walker.

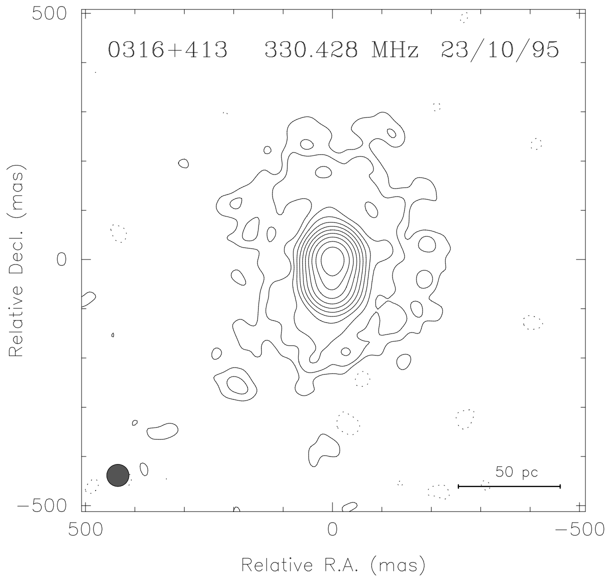


Figure 0.10: 330 MHz VLBA image of 3C84=NGC 1275, courtesy G. Taylor.

it very difficult either to follow up, or to see in other galaxies. The A+ configuration will be ideally suited to tracking down these sorts of objects, making believable maps of structures on *all* the relevant scales, and showing via spectral index mapping whether the suggested interpretation is indeed correct.

### 0.1.6 Synchrotron Emission & Gas Absorption at High Redshifts

The A+ configuration will be a significant boon for those studying galaxies at high redshift, because distance makes such galaxies small and weak, while the redshift makes their synchrotron emission difficult to observe at high frequencies. Indeed, this last is often used to select high-redshift galaxies by their radio spectral indices (cf. MILEY's stuff). The A+ configuration is ideally suited to imaging such systems, providing 125 mas resolution at 1.5 GHz, corresponding to 1 kpc or less at all redshifts for any reasonable cosmology; note that Richards' (1999) radio survey of the Hubble Deep Field found that all but one of the dozens of detected sources were extended, at this resolution. Imaging observations at radio wavelengths are interesting for any number of reasons:

- *To better understand the radio/optical alignment effect:* Optical observations of a number of high-z radio galaxies have shown that the optical tends to line up with the radio emission; in some cases significant Lyman-$\alpha$ emission is seen as well, indicative of large amounts of ionized gas (cf. VAN OJIK). The origin of this effect is not yet clear – are we seeing some reflection of highly-beamed light from the active nucleus? does the jet emanating from the radio galaxy somehow cause star formation as it interacts with the ISM? – but it will clearly be useful to take advantage of the enhanced sensitivity of the expanded VLA to make observations at the highest possible resolution, to see more details of this complex interaction.

- *To distinguish AGN from star formation activity:* Submillimeter observations are an excellent way to find very luminous sources, since whatever energy is emitted in a dusty system will mostly be re-radiated by that dust into the far infrared. However, that re-processing also hides the character of the underlying energy source, making it difficult to tell whether the emission is dominated by star formation, or by some compact central object. High-resolution radio observations can be very helpful: AGNs tend to be strong radio emitters, much more so than star-forming systems, and one can use the strength, the location, and the morphology of the radio source to distinguish between the two.

- *To study the far infrared/radio correlation:* One of the most intriguing results of the *IRAS* mission was the discovery of a tight correlation between radio continuum and far infrared emission in galaxies without AGNs. This is generally interpreted as an indication that star formation is the power source at both wavelengths, the radio emission resulting from cosmic ray acceleration in supernovae and supernova remnants, the FIR tracing dust re-radiation of the blue-ish stars which emit most of the luminosity. This clearly requires a reasonably constant initial mass function, and allows only a small scatter in magnetic field strengths between galaxies. The A+ configuration, combined with millimeter and submillimeter observations from MMA, will allow one to compare the radio with the far infrared emission in detail, to see whether the correlation holds in detail, and (if so) to constrain the diffusion rate of the cosmic ray electrons.

- *To map out magnetic field strength & structure:* Radio polarization measurements constrain both the orientation of the field lines (through synchrotron polarization) and the rotation measure along the line-of-sight (through Faraday rotation). This gives unique and fundamental information about magnetic fields at high redshift. High spatial resolution is vital to avoid beam depolarization, which can confuse or even obliterate the signal. There are already indications of very high rotation measures (and hence strong magnetic fields and/or very high electron densities) in a number of high-z sources.

- *To image H I absorption lines:* The combination of high spectral resolution and broad bandwidth coverage will make the Ultrasensitive Array[2] ideal for H I absorption line studies, with an expected $\gtrsim 45$ detections against random background sources in any 200 hour observation. If one can resolve these typically $\lesssim 1$ arcsec background sources, one can make detailed maps of both the distribution and the kinematics of the gas; A+ configuration is essential for such imaging.

- *To learn about galaxy environments:* Radio imaging offers several unique and fairly direct probes of the density of the medium surrounding a galaxy, even at high redshift. For instance, in Richards' combined VLA and MERLIN observations of the Hubble Deep Field, the source 3725+1129 is clearly a wide-angle tail source, suggestive of interaction with a substantial cluster environment. The MERLIN baselines – roughly the same as A+ configuration provides – were crucial to showing this, as the VLA data alone suggested a simple double. Relying on MERLIN in the future however is not a very useful option, as Richards had to observe for 30 days to match the sensitivity achieved by the *current* VLA in a few hours. Rotation measure studies were touched on above; Carilli has suggested that extreme rotation measure systems like BRI 11??+??? may indicate galaxy clusters which are already in place

[2] The Ultrasensitive Array refers to the first phase of the VLA Expansion Project, which will provide roughly microJansky continuum sensitivity ($1\sigma$ in 12 hours) at all frequencies between 1 and 50 GHz.

by $z = 2$. Although this last is clearly speculative, it is also obvious that the observations require some sort of 'cocoon' with large magnetic fields and large particle densities. Once again more detailed mapping by the A+ configuration will help constrain these models, and give further clues as to what is going on.

### 0.1.7 Variable Sources

Simply because of the bandwidth improvement, the 8-antenna A+ array will by itself have the same or better sensitivity as the entire current VLA, over the continuous frequency range from 1 to 50 GHz. The $uv$-coverage will also be fairly impressive, if one takes advantage of the typically 2:1 bandwidth ratios to perform multifrequency synthesis. With 10 times the best current resolution available continously, throughout the year, and the natural ability to filter out more extended structures, the A+ array will be the ideal monitoring instrument, measuring the light-curves of variable sources, responding rapidly to catch the earliest stages of sources like gamma-ray bursts, and providing consistent and detailed images of rapidly-developing Galactic transients (novae, superluminal jets). When combined with the VLA the A+ configuration will be even more powerful, with a sensitivity many times beyond any current telescope. The result will be a revolution in studies of radio variability; a few of the more obvious examples include:

- *Solar analogues:*
  The Ultrasensitive Array will detect for the first time the normal active levels of ordinary stars like the Sun. Most of the thousands of stars within 25pc should be detectable; at these distances the A+ configuration's resolution is better than 20 $R_\odot$, allowing actual imaging of this activity on the larger stars. Sub-milliarcsecond comparisons of optical with radio astrometry (see below) will give some positional information on flares even in dwarf stars.
- *Gravitational lenses:*
  Gravitational lens time delays offer one of the few direct determinations of the Hubble constant. Ideally, one would want continuous monitoring of many lenses to get many time delays and many detectminations of $H_0$. The A+ configuration would vastly increase both the number of lenses that could practically be monitored, and the quality of those monitoring observations, by
  - allowing continuous monitoring, unaffected by the VLA's changing configurations (currently one can observe only in A and B configurations, due to confusion amongst the lensed images in the smaller configurations)
  - resolving out much of the steep-spectrum extended emission, leaving a cleaner signal from the variable flat-spectrum component
  - detecting any milliarcsecond-scale structure in the lens images, providing vital constraints on the lens model (which is currently the major source of uncertainty in the determination of $H_0$). Here the improved surface brightness sensitivity (compared to MERLIN and the VLBA) helps enormously.
- *X-ray Transients: Relativistic Jets in the Milky Way*
  Radio follow-up observations of X-ray transients have led to some spectacular results, including the first clear correlations between X-ray and radio emission, tying accretion disk instabilities to relativistic particle ejection; the discovery of the first Galactic superluminal

jet sources (GRS 1915+105 [Mirabel & Rodríguez 1994], GRO J1655-40 [Hjellming & Rupen 1995; Figure ??], & 1748-288 [Hjellming *et al.*, *in prep.*); and the rapid imaging of the radio emission from a large number of these sources, showing that relativistic jets are typical byproducts of accretion onto massive, compact objects. The A+ configuration will make two fundamental contributions to these studies:

– *Imaging:*
Relativistic jets in the Galaxy expand so rapidly that they are resolved out by the VLBA in a matter of days; the VLA on the other hand, even when it happens to be in A configuration, can give only a crude idea of the distribution of the flux, which in any case often decays away entirely before being resolved (cf. Figure ??). The A+ configuration

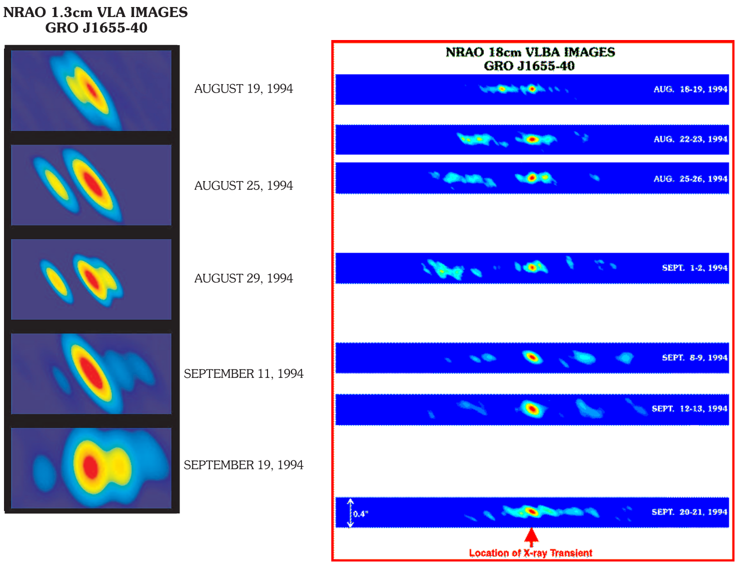


Figure 0.11: VLA 22 GHz (*left*) and VLBA 1.6 GHz (*right*) images of GRO J1655-40, a Galactic superluminal jet source (Hjellming & Rupen 1995). Note the time-scale. By the second epoch the source was so extended that the VLBA missed more than half the flux density, picking out only the smallest and narrowest features. Resolutions are 20-40 mas for the VLBA, 200-400 mas for the VLA.

will vastly improve the situation, primarily by (1) filling in the VLA/VLBA gap, allowing high-resolution images which are both accurate and recover all the flux; and (2) allowing high-resolution imaging of these sources *at all times*, regardless of the VLA's antenna configuration or VLBA scheduling constraints, and with a sensitivity comparable to the entire current VLA. This combination will give an unprecedented view of the full structure and evolution of relativistic jets, giving unique data on the precession of the jet and the decay rate of individual components, and allowing clear and unambiguous measurements of jet speeds and flux ratios.

– *Monitoring*
The A+ configuration is even more important for monitoring programs. The A+ configuration (working alone) will basically replace the GBI for monitoring observations,

providing continuous coverage with sensitivities comparable to the current VLA, over an even wider range of frequencies, with no confusion problems. We will thus obtain continuous, sensitive, multi-frequency (5 or more) radio light curves for months, for any transient as strong as those which have so far been detected. Such detailed light curves constrain theoretical models infinitely more tightly than the current 3-5$\sigma$ sprinkling of possible detections. Even without imaging we can learn the time offset between the radio ejection and the X-ray flare, whether there was a single or multiple outbursts, and whether the jets (assuming they are jets) are expanding freely; but since A+ provides imaging as well (see above) we can check these models directly, and see the evolution of a jet in more detail than has ever been possible before.

# Appendix A

# The VLA/A vs. A+ vs. the VLBA vs. MERLIN

```
VLA/A = VLA in A configuration (per OSS 1999)
MERLIN= MERLIN per latest MERLIN User's Guide (1995?!?)
VLBA  = VLBA per OSS 1999
VLA/A+= VLA plus 8 A+ antennas plus PT/LA, per 15feb99 Technical Goals
VLBA/A+= VLBA plus 8 A+ antennas plus 3 VLA dishes, guesstimate by mpr
         (I assume we get some extra tape decks for the VLA -- what the
         heck, no-one would even notice...)
All    = VLBA/A+ *plus* VLA/A+ (correlated independently, then added
         together)
All+++ = All *plus* VLA/B,C,D

Baselines:
  VLA/A    0.68 -  36.4km    ( 53.5:1)   Nant= 27 --> Nbase=  351
  MERLIN   6.4  - 217  km    ( 33.9:1)   Nant=  8 --> Nbase=   28
  VLBA   236    -8611  km    ( 36.5:1)   Nant= 10 --> Nbase=   45
  VLA/A+   0.68 - 350  km    (515  :1)   Nant= 37 --> Nbase=  666 (!!!)
 VLBA/A+ 150    -8611  km    ( 57.4:1)   Nant= 21 --> Nbase=  210
  All      0.68 -8611  km  (12,700:1)  Nant= 37+21 -> Nbase=  876
  All+++   0.035-8611  km (246,000:1)  Nant= 37+...-> Nbase= 1929
```

Resolution:

| | 1.5 GHz | 22 GHz* | 33 GHz** | 45 GHz |
|---|---|---|---|---|
| VLA/A | 1400 mas | 80 mas | --- | 50 mas |
| MERLIN | 140 mas | 8 mas | --- | ----- |
| VLBA | 4.3 mas | 0.31 mas | --- | 0.17 mas |
| VLA/A+ | 125 mas | 9 mas | 6 mas | 4 mas |

Sensitivity: (12hrs; microJy)

| | 1.5 GHz | 22 GHz* | 33 GHz** | 45 GHz |
|---|---|---|---|---|
| VLA/A | 6.6 microJy | 36 microJy | --- | 70 microJy |
| MERLIN | 60 | 400 | --- | ----- |
| VLBA | 38 | 123 | --- | 194 |
| VLA/A+ | 1.8 | 1.1 | 1.0 | 2.3 |
| VLBA/A+ | 18 | 57 | --- | 90 |

* 22 GHz is shown to reflect the best MERLIN resolution

** 33 GHz is shown to reflect the most sensitive high-resolution band at the (expanded) VLA

A couple ALMA comments:

- *Resolution:*
  - The current ALMA plan has 10–20km baselines and works from 30 to $\sim$ 1000 GHz.
  - Adopting 15km, this implies that ALMA matches the 45 GHz resolution of A+ configuration at about $(350/15) \times 45 = 1000$ GHz. ALMA's best 115 GHz (CO) resolution matches that of A+ configuration at 5 GHz; or the A configuration at $\sim 45$ GHz.
- *Sensitivity:*
  The Ultrasensitive Array has superior point-source sensitivity to the MMA for all sources whose flux declines with frequency ($\alpha < 0$); the MMA wins for all sources (including black-body emitters and stellar winds) whose flux increases with frequency ($\alpha > 0$). But they're fairly comparable for $-0.1 \lesssim \alpha \lesssim 0.1$, and for black-body sources. [This does account for typical (good) opacities, antenna efficiencies, etc.; I've assumed $64 \times 12$m antennas for the MMA.]

# Appendix B

# A One Page Summary of A+ Science

The new antennas of the A+ configuration actually create three instruments in one. When used with the VLA, the resolution will improve by more than a factor 10 over the current A configuration – an improvement similar to that achieved by HST, compared to ground-based optical imaging. With this resolution we could

- image both disks and jets in young stars several kpc from the Sun
- map SiO, H2O, and OH maser rings at 5–50 AU around red giants
- resolve even the faintest SNRs and HII regions in nearby galaxies
- separate starbursts from active galactic nuclei to z¿5 (requires sub-arcsecond resolution below 1 GHz)

The new antennas would also revolutionize VLBA science, by allowing the easy mapping of structures from a few to 100s of milliarcseconds. Currently the VLBA is limited both by the small number of antennas, and by having no baselines shorter than about 400km. At 4cm, this lack of short baselines renders all structures larger than about 20mas invisible to the current VLBA – it's as if we could see the tips of the waves, but not the underlying ocean. The VLBA can make exquisite images with milliarcsecond images, but may not 'see' 90% of the source flux; the VLA recovers the entire source flux, but with ¿10 times worse resolution. The A+ configuration would fill in this gap, providing reliable images with a spatial dynamic range of more than $10^4 : 1$ (by contrast, combining all four configurations of the current VLA gives a spatial dynamic range of only 500:1). With this new instrument we could

- reliably follow the evolution of superluminal jets emitted from black hole binaries anywhere in the Galaxy – even the best current VLBI images are severely compromised by missing progressively more flux (up to 90% after only a few days) as the source expands
- study the intermediate (10s of parsecs) scale emission from extragalactic jets – this is the scale on which many jets switch from one- to two-sided, i.e. begin to interact with the ISM
- make images at comparable resolution between 90cm and 7mm, yielding believable spectral indices & maps of obscuring material

So far we have discussed what A+ configuration could do for the VLA and for the VLBA; but the A+ antennas would themselves constitute a powerful imaging instrument, with sensitivity comparable to the current VLA, with 10 times better resolution. Too, this array would be available around the clock, every day of the year. This array would constitute the best instrument in the world for tracking radio transients; with it we could

- image all the novae in the Galaxy, regardless of when they go off, tracking their evolution from optically thick to thin, and providing direct estimates of the mass and clumpiness of the emitting regions
- image *all* Galactic X-ray transients, responding more quickly to X-ray satellite triggers and following sources more consistently than permitted by an all-purpose instrument like the VLA
- measure time delays for gravitational lenses more consistently and more easily, for smaller source separations
- track the radio light-curves of gamma-ray bursts (GRBs) at more frequencies, with much finer time sampling, to lower flux levels – this will determine GRB source sizes through scintillation, provide better statistics on the range of GRB light curves, and, by avoiding source confusion throughout the year, follow the GRB's evolution from ultrarelativistic to non-relativistic shock

The VLA Expansion Project increases the sensitivity and frequency coverage of the VLA enormously: a comparable improvement in optical astronomy would require moving from a 5m telescope with 1970s instrumentation, to a fully-outfitted 15m. But this is only half the story. The new antennas of the A+ configuration would also increase the resolution by more than a factor of ten. This corresponds roughly to the difference between Palomar and the Hubble Space Telescope. The expanded VLA will be as great an improvement over current radio instruments, as NGST will be over Kitt Peak's 4m.