The Contributions of the VLA to the Study of Radio Stars

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Abstract. This review[1] is a futile attempt to cover developments in the field of stellar radio astronomy (across the whole HR diagram) which have been influenced by VLA observations. The VLA has completely revolutionized the field; it can be argued that stellar radio astronomy would barely exist without the VLA. Different areas of physics and stellar astrophysics which can be addressed with VLA observations are mentioned, including the Sun (briefly). Among the major discoveries is the fact that many main–sequence stars like the Sun possess a nonthermal corona which is completely absent on the Sun.

1. Introduction

Stellar radio astronomers like to argue that the discovery that a huge range of stars of widely disparate types emit detectable radio emission is one of the major and unexpected breakthroughs made by the VLA. After all, the VLA was never expected to detect stars when it was designed: its primary goal was to be the spatial structure of extragalactic sources. Volume I of the original proposal for the VLA (dated January 1967; a copy may be found in the NRAO library) discusses the science expected to be done with the VLA in just 9 single–sided, double–spaced typed pages (out of several thousand pages in the whole document: by modern standards, the science justification was remarkably lightweight and nowadays would never pass muster). Over a third of this is devoted to extragalactic sources, but other topics mentioned include thermal galactic sources such as planetary nebulae and HII regions and solar system objects including the Sun. The only mention of a star (other than the Sun) is a reference to "stellar envelopes", which in modern parlance meant thermal stellar winds, and we shall return to that particular reference later in this review. (Note that the authors did cover themselves by remarking that "The capability of the VLA is so far beyond that of any existing instrument that it can be expected to open up vast new vistas and areas of research which cannot now be predicted." This was of course correct, although this statement too would probably be frowned upon by the modern reviewer for being too wishy–washy.)

Stars weren't included in the science justification (I assume) for the simple reason that there was no reason to expect them to be detected, certainly not main–sequence stars: it is a straightforward calculation to take the Sun, put it at the distance of the nearest known stars (the M dwarf Proxima Cen and the G dwarf solar analog α Cen at 1.3 pc) and show that you could not detect its steady emission (fluxes of order 15 μJy at 20 cm and 75 μJy at 2 cm). On that basis, the prospects for detecting "ordinary" stars even further away seem dim. However, by the time the VLA actually started observing 10 years later quite a number of stars had been detected by the generation of interferometers which operated through the 1970s (the NRAO 3–element interferometer and Westerbork) and which provided the positional discrimination missing from earlier single dish observations. Reviews of the state of the field at around the time when the VLA started operating may be found in Barlow (1979),

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Hjellming & Gibson (1980), and in Hjellming's (1988) comprehensive review. A number of hot mass–losing stars such as P Cygni, WR 140 and MWC 349 were comfortably detected at centimeter wavelengths, as were about 20 members of the class of evolved binary stars named after the prototypical system, RS CVn. Huge meterwave flares from M dwarf flare stars and microwave flares from red giants such as Betelgeuse were reported in single–dish observations, but were widely regarded with suspicion. And pre–main–sequence stars made up two of the weakest detections ever reported with the NRAO interferometer, T Tauri (8 mJy at 3 cm) and LkHα 101 (Spencer & Schwartz 1974).

So when the VLA started operating, certain classes of stars were already known to be radio sources, but with relatively few members of each class detected, and there were no radio detections of "ordinary" main sequence stars. Surveys of the classes known to provide detections were quickly started, as was work on the main sequence: Dave Gibson persuaded Paul Fisher to do his M. Sc. thesis on M dwarf flare stars, and the close association of solar and stellar groups in Boulder led Jeff Linsky, Dale Gary and George Dulk to look at a small number of active stars from a range of spectral types. Once these groups reported their detections (Fisher & Gibson 1981; Gary & Linsky 1981; Fisher 1982; Gary, Linsky & Dulk 1982; Linsky & Gary 1983) the field grew quickly, and subsequently almost every conceivable stellar class has been surveyed with the VLA.

The VLA has a number of properties which make it by far the preferred instrument for stellar radioastronomy: in addition to its excellent sensitivity, it has frequency agility which make it feasible to obtain a continuum spectrum for an object in a short time; it has high spatial resolution, which avoids confusion with the miriad of background extragalactic sources except in the most compact configuration at the lowest frequencies; and perhaps most important of all, its "Y" configuration together with the large number of dishes produce excellent snapshot *uv* coverage, which means that a given target field can be mapped adequately in a few minutes, something simply not feasible with a linear array. The latter property makes the VLA unmatched at carrying out surveys, and for studying time–varying phenomena which occur on stars as well as on the Sun.

As mentioned earlier, we now know that many main–sequence dwarf stars are unexpectedly strong radio sources, because they possess something completely unknown on the Sun, a nonthermal corona: this discovery constitutes a major advance in our understanding of stellar atmospheres. The VLA has completely transformed the field of stellar radioastronomy, and observations with the VLA are the foundation of virtually all advances in this field. In the remainder of this paper I will try to cover some of these advances. This will not be a comprehensive review, and the material presented is necessarily biassed by my own interests and by the availability of figures. I apologize in advance for the fact that for lack of time I will omit some references which deserve to be included. I will not cover at all the important work done on systems containing compact objects such as neutron stars or black holes, even though some of the brightest "stellar" radio sources (e.g., Cyg X–3) fall into this category. I will at the end briefly mention solar work carried out with the VLA, since it is not covered elsewhere in these proceedings.

I will assume a passing acquaintance with the basic properties of the main radio emission mechanisms. *Thermal free–free* or *bremsstrahlung* emission is responsible for the classic stellar–wind radio emission. The opacity for this mechanism varies as $n_e^2\,T^{-1.5}\,\nu^{-2}$, where n_e is the electron density, T the electron temperature and ν the radio frequency. The fact that the opacity decreases as frequency increases, while density in an outflow decreases with radius, leads to a fundamental property of free–free radio emission from stellar winds: higher frequencies probe deeper into the stellar wind. For a constant–velocity wind ($n_e \propto r^{-2}$) the radius of the optically thick surface, which limits how deeply we can see, scales with frequency as $\nu^{-0.7}$. The combination of this scaling of optically–thick source dimension with frequency and the ν^{+2}–dependence of the black–body emission law produces the classic $\nu^{0.6}$ spectrum of a constant–velocity free–free–emitting stellar wind. *Nonthermal synchrotron emission* is the basic microwave emission process operating in solar flares and in stars which show solar–like magnetic activity. This mechanism requires nonthermal distributions of mildly ("gyrosynchrotron") or highly ("synchrotron") relativistic electrons in magnetic fields of order gauss or stronger. With magnetic fields of hundreds of gauss which are typical of stellar coronae, this mechanism can have a spectral peak (corresponding to the transition from optically thick at low frequencies to optically thin at high frequencies) in the microwave range, as observed for solar flares. For much lower magnetic fields, such as one expects outside stellar atmospheres, this mechanism should be optically thin at VLA frequencies and the radio spectral index $-\alpha$ is then related to the nonthermal electron energy spectral index $-\delta$ by the synchrotron relationship $\alpha = (\delta - 1)/2$.

2. The Radio HR Diagram

To emphasize the changes in our knowledge of the radio properties of stars, Figure 1 presents a sample of the *radio–detected* stars plotted on an HR diagram (an idea which goes back at least to Gibson 1985). Stars believed to be nonthermal emitters are shown with filled symbols, while thermal emitters are shown with open symbols. Recall that prior to the VLA this figure showed a number of cool subgiants in binary systems, a few hot luminous stars, two pre–main–sequence objects and possibly some M dwarf stars. The detections presented in Figure 1 cover virtually the whole of the HR diagram where stars are found, with the possible exception of ordinary main sequence A stars (see below), isolated white dwarfs and brown dwarfs. Figure 1 contains by no means all the stars detected by the VLA: I did not have time for a complete survey of the literature, and an HR diagram is necessarily restricted to stars for which reliable absolute magnitudes and colors are available. This is not yet possible for many classes of less well known objects, such as the stars identified in *ROSAT* X–ray surveys which are believed to be runaways from the Taurus star–forming region (e.g., Carkner et al. 1997).

As is readily apparent, this restriction (reliable magnitudes and colors) had to be relaxed for some classes, notably hot stars, symbiotic and Be stars, and classical T Tauri stars: all these classes of object tend to lie in heavily obscured areas, which affects both colors and magnitudes, while the catalogued distances to the more luminous stars are usually just estimates. I have attempted to correct the colors and magnitudes of the hot stars for extinction where data are available (although this is to some extent a circular procedure since the appropriate corrections are often determined by assuming that a star of a given spectral type should lie at a particular place on the HR diagram). I have not attempted to separate binary components in spectroscopic binaries. For the Algol systems the hot primary generally dominates the light and the plotted position is that of the primary; for the RS CVn systems, the two stars often have similar magnitudes but different colors, so that the position of these systems on the HR diagram does not accurately represent either component. Wherever possible, Hipparcos data have been used for M_V and $B - V$: this applies to nearly all stars with $M_V > -2$.

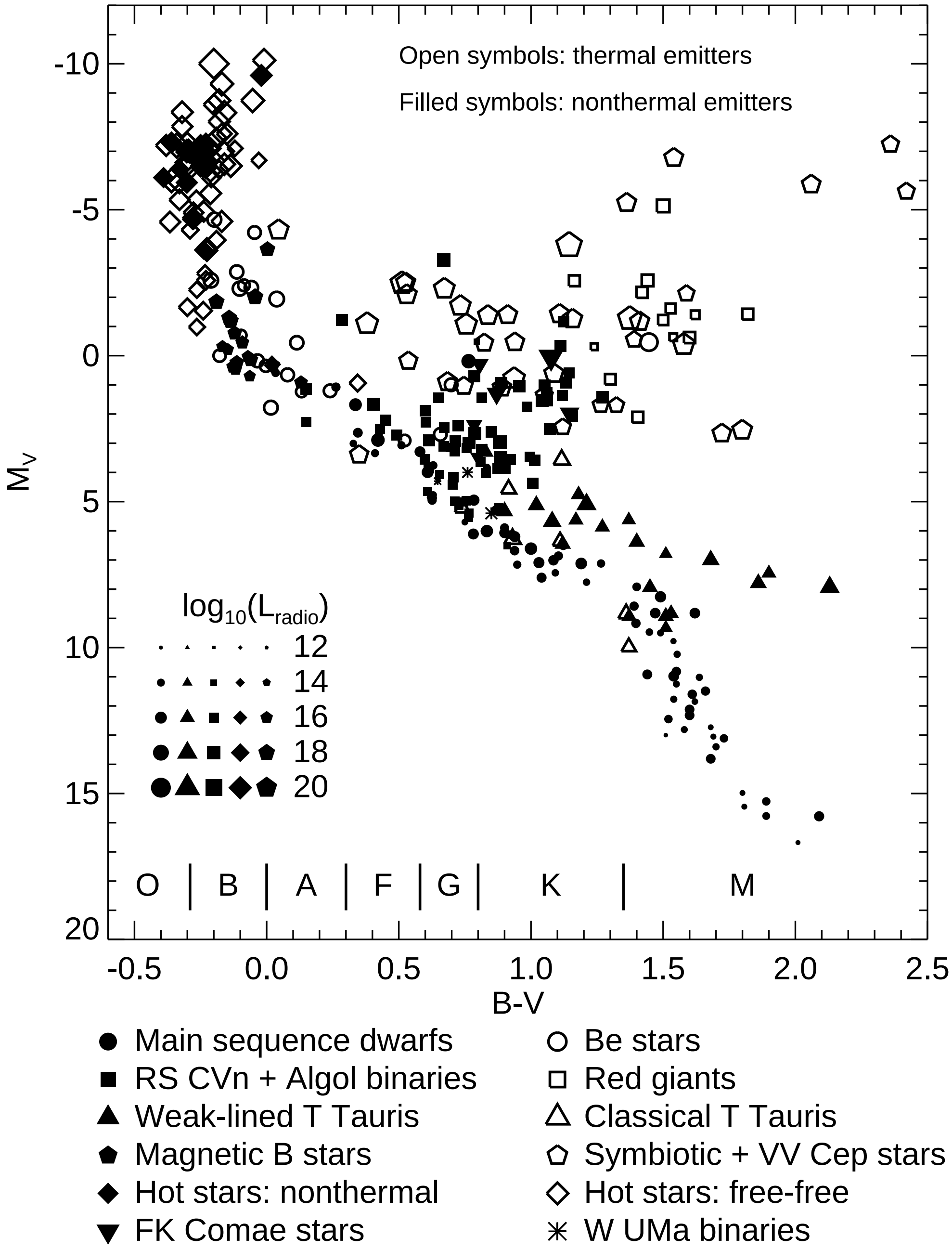

Figure 1. An HR diagram for stars detected as radio emitters, compiled from the literature using the Hipparcos catalog for the luminosities and colors wherever possible. For hot stars corrections for extinction have been applied where available. The size of the symbol reflects the radio luminosity of the star as labelled (in ergs s^{-1} Hz^{-1}). The diagram is restricted to stars for which distances are available, and therefore shows only a small (but reasonably representative) sample of all the stars detected by the VLA. Stars believed to be nonthermal emitters are represented by filled symbols, while thermal emitters are shown by open symbols. A color version of this figure may be found on the web at http://www.astro.umd.edu/~white/images/radio_hr_diag_full.gif.

The following sections will highlight the radio properties of different classes of star within this diagram.

3. Luminous Hot Stars

Large numbers of very hot luminous stars are now known to be radio sources, thanks to surveys of OB stars (Bieging, Abbott & Churchwell 1989; Leitherer, Chapman & Koribalski 1995; Scuderi, Panagia & Umana 1998) and Wolf–Rayet stars (Abbott et al. 1986; Leitherer, Chapman & Koribalski 1997). On theoretical grounds most very luminous hot stars should be detectable via the free–free emission from their dense powerful winds, and the spectra of the radio emission of most of these stars is consistent with this interpretation (which implies the $\nu^{0.6}$ spectrum of an optically–thick stellar wind). However, there is a significant fraction which have radio spectra incompatible with free–free emission, and these stars are believed to exhibit nonthermal synchrotron emission which gives us information on conditions within the winds of these stars. The interpretation is that the nonthermal emission is produced by electrons accelerated at shocks which form in the inhomogeneous winds: the characteristic speed of a hot star wind is generally in excess of the ambient sound speed in the wind, so that any significant velocity fluctuation, such as a fast knot overtaking a slower one or two winds colliding, has the potential to result in a shock. Once a shock forms, electron acceleration apparently takes place (by an as yet not completely understood mechanism). A high Mach–number shock produces a characteristic power–law energy distribution of spectral index -2, which results in a $\nu^{-0.5}$ radio flux spectrum (in the optically–thin limit believed appropriate to these sources). A detailed model for nonthermal emission from a single–star wind carrying random shocks was worked out by Rick White (1985). Note that the acceleration must take place at some distance from the star: the powerful radiation field of a hot star can quench shock acceleration close to the star where the inverse–Compton mechanism depletes energy from a high–energy electron faster than a shock can supply it (Chen & White 1994). This is a mild problem for models in which the magnetic field in the synchrotron source is a stellar field carried out by the wind, since it will diminish with distance from the star. An alternative is for the magnetic field also to be generated in the shocks as a byproduct of the plasma turbulence there.

We will discuss two particular stars in more detail, as examples of thermal and nonthermal sources with particular historical importance.

3.1. MWC 349

MWC 349 became famous amongst radio astronomers as probably the strongest thermal radio source in the northern sky, and an important example of a stellar wind. It is one of the most extreme galactic members of the class of luminous B stars showing forbidden emission lines, known as B[e] stars. These stars are characterized by very strong Balmer lines, forbidden FeII lines and very strong emission from hot dust at infrared wavelengths. These features are assumed to derive from the combination of a very dense equatorial disk, which provides the Balmer emission and the dust, together with a powerful ionized polar outflow which is responsible for the forbidden lines. MWC 349's radio spectral index of +0.6 motivated the fundamental theoretical work on the radio spectra of stellar winds (Olnon 1975; Panagia & Felli 1975; Wright & Barlow 1975). While the first models assumed a spherically–symmetric wind, observations with the VLA have shown that this is not appropriate (Cohen et al. 1985; White & Becker 1985; Rodríguez & Bastian 1994). On a scale of arcseconds (left panel of Fig. 2) the radio source is resolved with pronounced polar and equatorial axes of symmetry. At higher spatial resolution (right panel) the core is seen to break up into two sets of curved "horns" on either side of the star with much weaker emission in between. The peak brightness

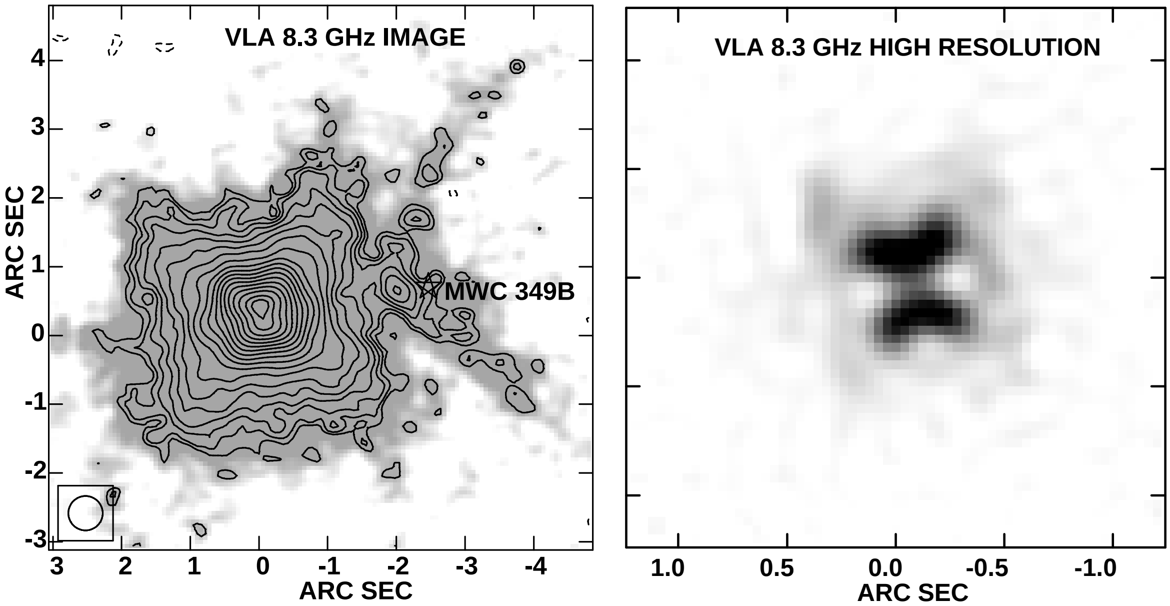

Figure 2. VLA 8 GHz images of the famous thermal stellar–wind source MWC 349, a B[e]star. The left panel shows a naturally–weighted cleaned image intended to emphasize weaker features: in addition to the thermal emission from MWC 349 itself, a weak bow shock is seen at the location of the interaction with the wind of a B star companion, MWC 349B. The polar axis of the system is slightly left of vertical, and the equatorial plane is nearly orthogonal to the plane of the sky. The right panel shows a super–resolved maximum–entropy deconvolution of the same visibilities in which high spatial resolution is achieved in the region of strongest flux (data of Rodríguez & Bastian 1994).

temperature in the horns is 10^4 K, while it drops to 4400 K at the inferred position of the star. The interpretation of this image is that the outflow from MWC 349 has low velocity but high density in the equatorial plane (the low–brightness region between the horns), and higher velocity but lower density in the polar directions (the directions of the horns). The density is so high in the equatorial plane that the gas there has completely recombined and is neutral, while in the polar directions the gas is still ionized and thus can be optically thick at the temperature characteristic of a photo–ionized wind (10^4 K).

MWC 349 is also notable as one of the few stars whose thermal emission is strong enough for high spatial resolution recombination line observations to be carried out with the VLA (Martín–Pintado et al. 1993; Rodríguez & Bastian 1994). At millimeter and shorter wavelengths these recombination lines become extraordinarily bright due to maser action (associated with the fact that the rate of downward transitions of a recombining electron as it drops down the energy–level ladder increases as it gets to lower and lower levels) and this effect has opened up a whole new field of research (e.g., Martín–Pintado et al. 1989; Thum et al. 1994; Strelnitski, Ponomarev & Smith 1996).

3.2. WR 140

No discussion of stellar observations by the VLA would be complete without a mention of the star HD 193793, also known as WR (i.e., Wolf–Rayet) 140, which Barry Clark faithfully scheduled for Rick White and Bob Becker once per month for 8 years. The results of this effort are plotted in Figure 3, from White & Becker 1995, and they demonstrate how much physics can be addressed by a simple set of radio light curves for an unresolved system. WR

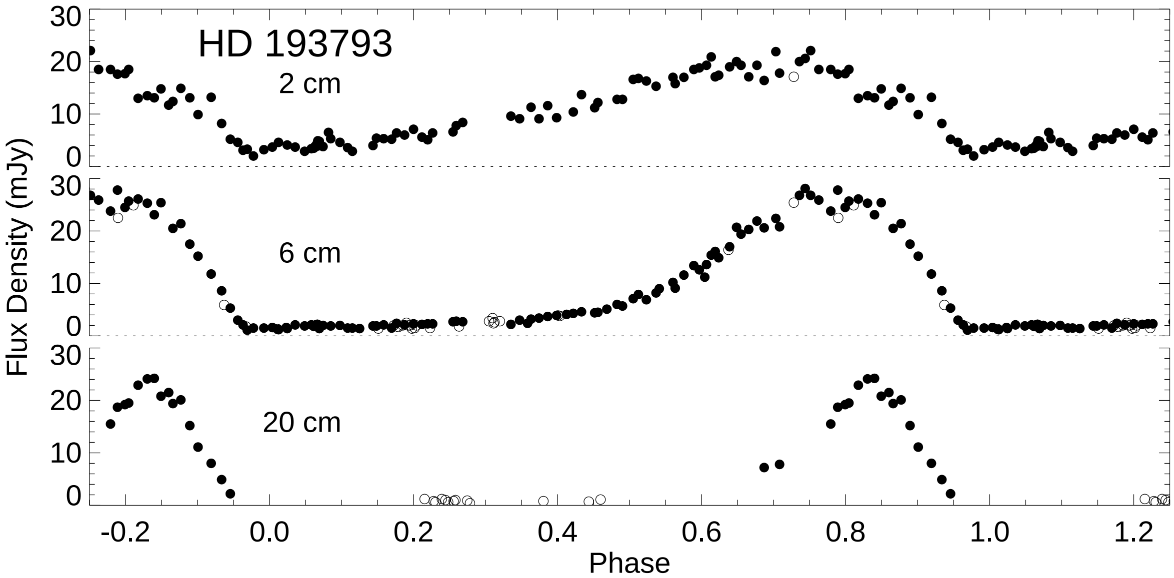

Figure 3. The radio light curve for WR 140 plotted against orbital phase over the 7.9–year orbit at each of three wavelengths. Filled circles are VLA data taken every month by White & Becker (1995); open circles represent other data compiled by Williams et al. (1990) covering more than one cycle, indicating that the light curve repeats almost perfectly from one cycle to the next. (Figure provided by Rick White.)

140 consists of a (secondary) WC7 Wolf–Rayet (WR) star and an O4-5 star (primary) in a highly elliptical orbit with a period of 7.9 years. It was known to have a nonthermal radio spectrum before the VLA began operating; the VLA's characteristics made it possible to monitor the evolution of the radio spectrum of this source using just a modest amount of observing time per month.

The basic model is that the nonthermal emission arises due to synchrotron emission from energetic electrons accelerated in the shock where the powerful winds from the two stars collide. There is also some free–free emission from the winds, and the nonthermal radio emission is modulated by free–free absorption as the location of the shock changes with respect to the winds. The shock strengthens near periastron and weakens near apastron. The orientation of the orbit is such that the O star is closest to us during most of the orbit; the WC7 star passes between us and the O star just after periastron, at phase 0.01. The O star wind has a terminal velocity of 3100 km s^{-1} with $\dot{M} = 1.8 \times 10^{-6}$ M$_\odot$ yr^{-1}, while the WR wind has a velocity of 2600 km s^{-1} with $\dot{M} = 6 \times 10^{-5}$ M$_\odot$ yr^{-1}. In principle, to model this system one needs to know all the physical properties of the binary orbit and the winds, and understand the shock physics and its variation with stellar separation, electron acceleration at the shock, the source of magnetic fields and absorption in the wind; conversely, all these phenomena affect the radio light curves.

Free–free absorption should be largest at the lowest frequency and the 1.5 GHz light curve is consistent with this expectation: it shows no significant flux except for a narrow peak near phase 0.8. At 5 GHz the peak is much broader, with only weak emission just after phase zero when the strong wind of the WR star is between us and the wind–interaction region. The 15 GHz emission, which should suffer the least absorption and therefore best represent the intrinsic emission profile, peaks at phase 0.70, somewhat earlier than the 1.5 GHz peak: between phases 0.70 and 0.85 the 15 GHz flux drops while the 1.5 GHz emission rises. From phase 0 to 0.5, the spectral index is positive, consistent with thermal free–free emission.

The fact that there is any 1.5 GHz emission detected at all is difficult to explain, since the parameters for the WR wind imply that it should be optically thick at 1.5 GHz well outside the binary orbit. Williams et al. (1990) showed that a model with spherically–symmetric winds could not explain the light curves and argued that the shadow of the O star creates a cavity in the WR wind where the opacity is greatly reduced. White & Becker (1995) argued that even the O star wind will be optically thick and absorb any high-brightness-temperature nonthermal 20 cm emission behind it; they suggest instead that the WR wind is confined to an equatorial plane inclined with respect to the orbital plane. In this geometry the WR wind sweeps across the position of the O star twice per orbit; one of these occasions is presumably at phase 0.70, where the radio flux is maximum. The number of possible factors playing a role in these simple radio lightcurves demonstrates just how much physics can be addressed with them.

4. Be stars

Be stars are stars of spectral type B which show strong emission lines indicating the presence of circumstellar material. They have strong infrared emission indicating the presence of dust, and all the evidence points to the presence of disks around these stars. This description by itself includes a very disparate array of stars, including the B[e] stars mentioned above: here we use the term to cover two types of stars. The *classical Be stars* are of uncertain evolutionary status. They are believed to be rapidly rotating, and may be a natural evolutionary state of all B stars. A number of classical Be stars have been detected in surveys by the VLA, and appear to have radio spectral indices intermediate between the thermal stellar wind value of +0.6 and the optically thick bounded source value of +2.0 (Taylor et al. 1990; Dougherty, Taylor & Waters 1991). Some Be stars are well–known for their association with neutron stars in close binaries which are strong X–ray and sometimes radio sources (notably LSI +61° 303).

A subset of the Be (and Ae) stars is found in regions of current star formation and is associated with reflection nebulosities. These stars are known as *Herbig Ae/Be stars*. The class consists of young massive stars which have only recently formed. They are the several–solar–mass counterparts of T Tauri stars (stars of age of order 10^6 yr and mass less than 1 $M_\odot$). These stars have dusty disks and energetic outflows. VLA surveys have detected more than ten of these stars and the radio emission is believed to be thermal free–free emission from the outflows (Skinner, Brown & Stewart 1993; Di Francesco et al. 1997).

5. Symbiotic stars and VV Cephei binaries

Symbiotic stars are interacting binary systems consisting of a cool star and a hot star, with the cool component usually being a late–type giant and the hot component a white dwarf. VV Cephei–type binaries are similar in that they consist of a cool supergiant and a B main–sequence star, and are generally not interacting. Most single cool giant (or larger) stars are not notable radio sources because even though they may have strong stellar winds, the supply of ionizing photons from the red star is insufficient to maintain high degree of ionization in the outflow and the neutral wind then produces no continuum radio flux. Symbiotic stars and similar systems get around this problem by having a hot companion star to supply the ionizing photons which allow the outflow of the cool giant to become a radio source (Seaquist, Taylor & Button 1984; Taylor & Seaquist 1984).

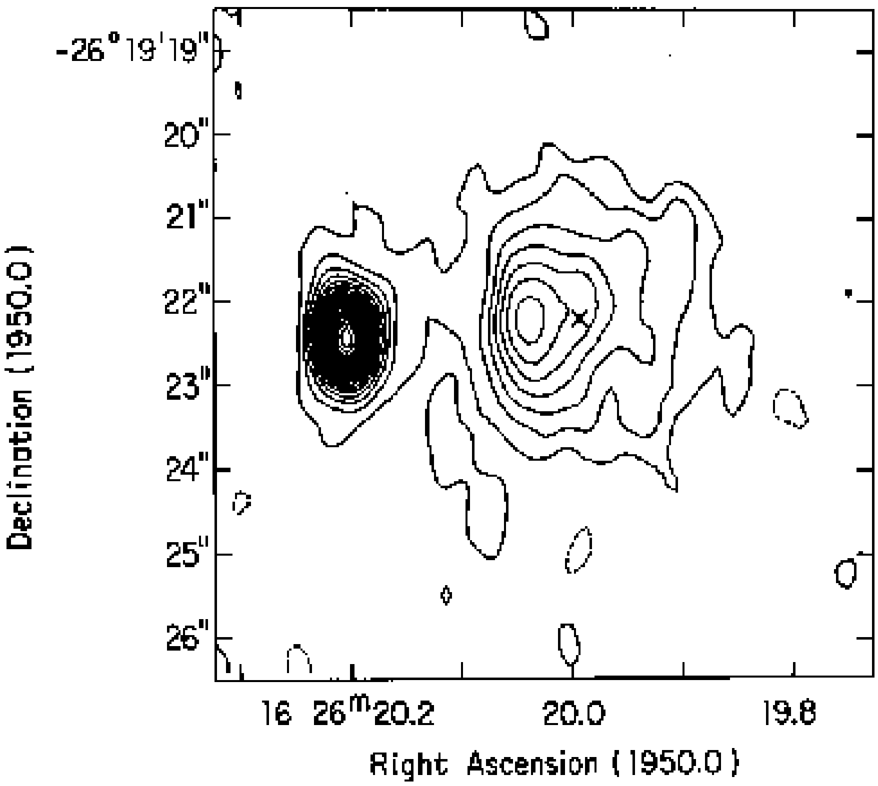

Figure 4. VLA 4.9 GHz image of Antares made from tapered A+B+C configuration data (Hjellming & Newell 1983). The cool M1.5 supergiant star is located at the unresolved source to the left of the image; the B2.5V star is located at the cross. The extended source around the B star can be well fit by a model of the subregion of the stellar wind from Antares which is ionized by Lyman continuum photons from the B star.

The relatively nearby VV Cep–like system Antares (M1.5 Iab + B2.5V) illustrates this effect beautifully: the early VLA image of Hjellming & Newell (1983; Figure 4) shows a compact optically–thick thermal source associated with the M supergiant while $3''$ to the west lies a diffuse extended optically–thin radio nebula associated with the B star. The compact source associated with the M star is just the disk of the star, similar to the emission from the single M supergiant Betelgeuse (see section 10), while the diffuse source represents the region of the M supergiant's dense wind which is ionized by ultraviolet photons from the B star. As expected for an r^{-2} density dependence in the cool star's wind, the diffuse source is asymmetric about the B star, being brighter on the side closest to the M supergiant (i.e., the higher density side). Seven VV Cep–like systems have been detected as radio sources: most have shorter binary periods than Antares and hence the density at the site of the B star is higher, giving larger optical depths, than for Antares (Hjellming 1985).

Surveys of symbiotic stars by Seaquist et al. (1984), Seaquist & Taylor (1990) and Seaquist et al. (1993) make up the bulk of the symbiotic detections shown in Fig. 1; note that since symbiotics are evolved binaries in which the two components have very different properties and often lie in obscured areas, their positions on the HR diagram have little meaning. Roughly half of the 99 symbiotics observed have been detected as radio sources. There is a formal correlation between the UV luminosity of the system and the radio luminosity, in accordance with the idea that the radio emission comes from a region of the cool–star wind ionized by the hot star (Seaquist & Taylor 1990). Most symbiotics do not show variability

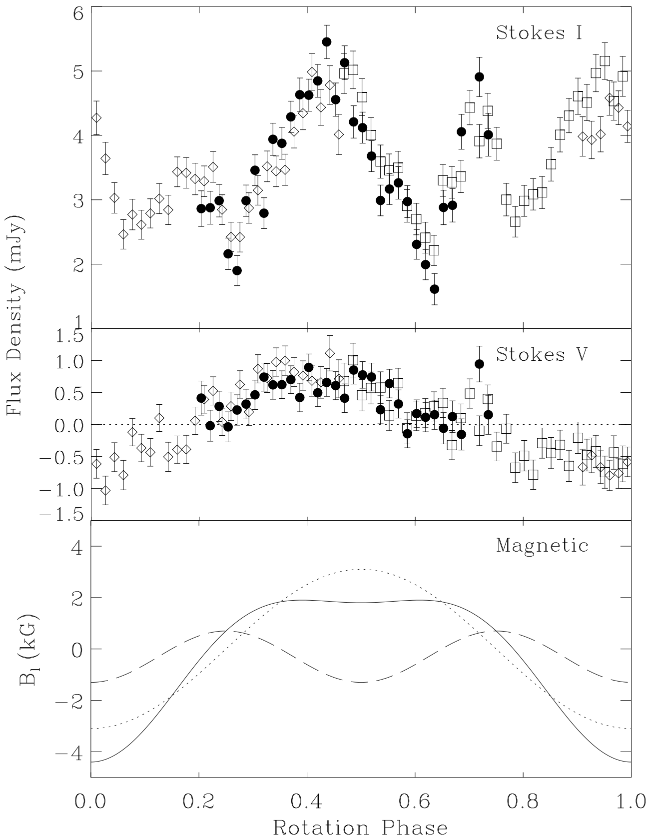

Figure 5. Radio and magnetic light curves for the magnetic Bp star HR 5624 plotted as a function of the phase of the 0.88 day rotational period. This star has a prominent quadrupolar component to its magnetic field in addition to a dipolar component: the bottom panel shows how the (optically) measured longitudinal field (solid line) for this star varies as a function of rotation phase, together with a decomposition into dipolar (dotted) and quadrupolar (dashed) components. The upper two panels show how the 5 GHz radio emission total intensity (upper panel) and circularly polarized flux (middle panel) vary as the star rotates (Lim, Drake & Linsky 1996). The three different symbols represent observations on three different days (spaced 2 days apart), showing that the modulation is repeatable.

in their radio flux, although there are some notable exceptions (e.g., the system HM Sge which shows a resolved shell, and may be due to interacting stellar winds rather than a cool wind ionized by a hot star: Purton, Kwok & Feldman 1983; Kwok, Bignell & Purton 1984). The radio spectra are often rising through the microwave range and flattening at higher frequencies: if the turnover frequency can be determined, the binary model for symbiotics permits an estimate of the binary separation (Seaquist & Taylor 1990).

6. Magnetic B and A stars

The class of early–type stars known for the chemical peculiarities in their photospheric spectra, and for the kilogauss magnetic fields which they possess, is a remarkably prolific and poorly understood supplier of radio sources. Surveys by Drake et al. (1987), Willson et al. (1988), Linsky et al. (1992) and Leone et al. (1994) have detected 25 of these stars (known variously as chemically–peculiar A and B stars, Ap/Bp stars or magnetic A and B stars). The chemical peculiarities are believed to result from gravitational stratification effects in the non–convective outer layers of these hot stars, while the magnetic fields are thought to be fossil fields left over from the collapse of the stars out of magnetized molecular clouds. The magnetic field geometry is usually dipolar, with the magnetic axis often offset from the rotation axis in what is known as the “oblique rotator” configuration.

This class of stars can be broken into four subclasses on the basis of different chemical properties, roughly corresponding to different temperature ranges: Helium–strong (He-S) stars (typically spectral types O9 – B5), Helium–weak (He-W; B5 – A0), Silicon (Si, also B5 – A0) and SrCrEu (the coolest subclass, spectral type A). Radio detections have been found amongst the three hotter subclasses, but not amongst the SrCrEu stars (Drake, Linsky & Bookbinder 1994). As a general rule, the earlier spectral types have much larger luminosities: σ Ori E (B2V) has a 5 GHz luminosity of $10^{17.9}$ ergs s^{-1} Hz^{-1}, while θ Aur (A0) is at $10^{14.7}$ ergs s^{-1} Hz^{-1}. Linsky et al. (1992) argue that the radio flux is related to the stellar winds: the mass loss rate (presumably driven by radiative flux) increases as one goes to earlier stellar types, so that the outflow provides a source of free energy available to generate a radio source. The favored mechanism is based on the Havnes & Goertz (1984) model for the magnetospheric structure of these stars. The interaction between the dipolar magnetic field and the strong stellar wind results in regions of high–density plasma trapped in the equatorial zone where the non–radial magnetic field inhibits outflow. Since the magnetic field energy density falls off rapidly with radius, at some point in the outflow the thermal energy density of the plasma will overwhelm the magnetic field and drag it outwards, resulting in the formation of a current sheet where acceleration of particles to nonthermal energies can take place. Accelerated electrons can then radiate by the gyrosynchrotron process in the strong magnetic fields nearer the star: observed high degrees of circular polarization are consistent with such a mechanism.

An interesting aspect of this class of stars is that their radio properties are quite similar to those of active cool stars: their radio spectra are typically fairly flat (Linsky, Drake & Bastian 1992; Leone, Umana & Trigilio 1996), their quiescent emission shows moderate degrees of circular polarization, and one of them has even been observed to show a radio flare with variability on timescales of minutes (Drake & Linsky 1989). Yet in the case of active cool stars the radio emission is believed to be produced by processes ultimately tied to the generation of complex magnetic fields in a dynamo associated with convection, which Ap and Bp stars, with their radiative interiors, should not produce. On the other hand, unlike radio–bright cool stars their X–ray luminosities are relatively weak (Drake et al. 1994), radio flares are clearly not common and the properties of the radio emission seem to be quite stable on long timescales. Some of these stars are just bright enough to be able to look for rotational modulation of the radio light curve with the VLA, and such modulation has been found (Leone & Umana 1993; Lim, Drake & Linsky 1996; Lim, Drake & White 1998), including modulation of the degree and sense of polarization (an example is shown in Figure 5). This is an important result because the characteristics of the modulation can be used to infer the magnetic geometry of the emitting region.

7. Pre–main–sequence stars

This has been a productive area for the VLA which overlaps with interstellar medium (e.g., star formation and molecular cloud) studies. Probably over one hundred stars belonging to this class have now been detected (Cohen, Bieging & Schwartz 1982; Bieging, Cohen & Schwartz 1984; André, Montmerle & Feigelson 1987; Stine et al. 1988; O'Neal et al. 1990;

White, Pallavicini & Kundu 1992a; Chiang, Phillips & Lonsdale 1996; Suters et al. 1996; Carkner et al. 1997; White et al. 1998; Stine & O'Neal 1998). Some rich areas of low–mass star formation may contain many detected radio stars in a single VLA 5 GHz primary beam (Leous et al. 1991; Felli et al. 1993).

In evolutionary terms there are at least three stages during star formation which are important for radio studies. First are the so–called "Class 0" sources, which are highly embedded, presumably very young stars, not visible in the optical but often the source of molecular outflows and optically–visible Herbig–Haro jets. These sources are often very weak microwave continuum sources, which has proven to be a useful property since VLA observations can then be used to identify the exact location (with high spatial resolution) of the source of an outflow which is otherwise obscured (e.g., Pravdo et al. 1985; Curiel et al. 1990; Leous et al. 1991; Anglada et al. 1994; Bontemps, André & Ward–Thompson 1995; Rodríguez, Anglada & Raga 1995; Anglada 1995; Rodríguez & Reipurth 1996). Even the outflows associated with stars in this stage have proven to be detectable with the VLA: thermal jets indicating the presence of ionized gas in the outflows (Hughes 1989; Curiel et al. 1993; Rodríguez et al. 1994; Martí, Rodríguez & Reipurth 1995; Torrelles et al. 1997) and, even more remarkably, synchrotron emission indicating that acceleration of electrons to very high energies must be taking place in the outflows, possibly at the site of shocks (Yusef–Zadeh et al. 1990; Reid et al. 1995), have been observed with the VLA.

The next evolutionary stage corresponds to the classical T Tauri stars (CTT): low–mass stars found in star–forming regions which are generally optically visible but with veiling of the optical spectra. They are often associated with optical nebulosity and tend to show infrared excesses attributed to the presence of dust disks. The disks are interpreted to be remnants of the accretion process which formed the star. CTT's lie above the main sequence on the HR diagram, indicating that they are still contracting. Typical ages are thought to be 0.1 – 2 million years. The CTT stars which have been detected as microwave continuum radio sources typically show spectra rising at microwave frequencies which suggest an origin as free-free emission from an ionized outflow. At higher frequencies the dusty disks themselves become strong radio sources, and several VLA observations have spatially resolved these disks, allowing their physical parameters to be determined (e.g., Rodríguez et al. 1992; Wilner, Ho & Rodríguez 1996). Note that reddening corrections have not been applied to the CTT stars on Fig. 1, which accounts for their erratic distribution on the figure.

Members of the third class of low–mass pre–main–sequence stars are called weak–lined T Tauri (WTT) stars. They are apparently very similar to classical T Tauri stars, i.e., lie in the same region of the HR diagram, but they lack the signs of circumstellar material which are characteristic of CTTs (infrared excess, optical veiling). They are also called "naked" T Tauri stars for this reason. Not surprisingly, since they are young, generally rapidly–rotating cool stars, WTT's have radio properties similar to those of active main sequence stars: they tend to be very strong nonthermal radio sources (luminosities of order 10^{17} ergs s^{-1} Hz^{-1}, i.e. much larger than active main sequence stars of the same spectral types), but with lower degrees of circular polarization detected than on most other active stars and apparently quite long timescales for radio variability (White, Pallavicini & Kundu 1992b). It is notable that despite the similarities in the underlying stars, including similar X–ray luminosities, no confirmed classical T Tauri star has ever (to my knowledge) shown any evidence for nonthermal radio emission. It may be that the stellar activity which leads to nonthermal coronae in WTT stars is somehow suppressed in CTTs by interaction with the circumstellar material close to the star, or else the nonthermal corona exists close to the stellar surface, but the radio emission

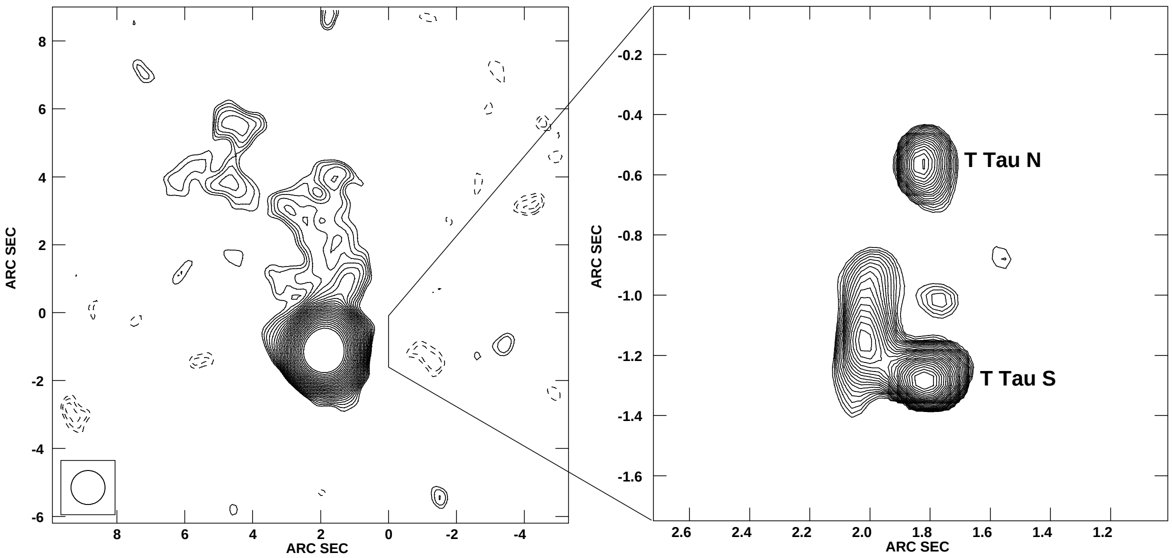

Figure 6. VLA "A"–configuration images of the T Tauri system (White et al, in preparation). Left panel: a 4.5 GHz image made using a 1″ beam to emphasize the larger–scale structure. The stars are located in the core of the brightest emission. Extended emission is seen trailing off to the north–east. Right panel: a super–resolved maximum–entropy deconvolution of the 8 GHz emission in the core of the system, showing emission from the two stars (labelled) together with quite bright extended emission to the north–east of T Tau S. The morphology of the extended emission seems to change with time.

from it is unable to penetrate a cloak provided by cool but ionized gas at greater distances from the star, which may be optically thick even without being bright enough to be observed itself (Montmerle & André 1988).

The prototypical system T Tauri displays a number of remarkable features all by itself. As noted earlier, it was detected as a radio source before the VLA was built, and its (relatively) strong radio flux allows it to be studied in some detail. VLA observations were instrumental in showing that in fact it is a binary system consisting of two stars 0.6″ apart (Schwartz et al. 1984): both are radio sources. The optically visible star is the northern component, and is a classical T Tauri star with a rising microwave spectrum and a dusty disk detected at millimeter wavelengths. The southern companion is embedded, but is also detected as an infrared source: its radio characteristics are those of a WTT star (nonthermal spectrum, circular polarization, variability: Skinner & Brown 1994; Phillips, Lonsdale & Feigelson 1993). In addition to the two stellar sources, there is also extended radio continuum emission in the system on small scales, between the two stars (Schwartz, Simon & Campbell 1986; Ray et al. 1997), and on a larger scale corresponding to the optical nebulosity associated with the system (see Figure 6). The nature of this extended emission is not yet well understood.

8. RS CVn and Algol binaries

Since most of the confirmed radio stars known when the VLA started observing were RS CVn systems, it is natural that they received a great deal of attention from VLA observers. RS CVn binaries are detached but close binaries in which at least one component has evolved into a cool subgiant, typically consisting of an F – G main sequence primary and a K subgiant or giant which was the primary in the system until it evolved away from the main sequence.

During their main–sequence life these systems may have been quite inactive, consisting of two stars each typically with a mass in excess of a solar mass. Once the original primary depletes its core hydrogen, it moves into the Hertzsprung gap and develops a convection zone as it cools. The combination of the rapid rotation enforced by corotation in the binary and the presence of a convection zone leads to the generation of intense solar–like magnetic activity. The activity is thus attributed to the cooler evolved component of the system. Most single cool subgiants do not show similar levels of activity due to their slow rotation (exceptions being the small number of FK Comae systems discussed in section 10).

The RS CVns are the most prominent members of a broader class of active close binaries containing a cool star (Strassmeier et al. 1993). These include the optically bright Algol systems, which contain a hot star and a cool star (typically a B or A primary and a G − K subgiant secondary) in a close binary. The mass ratio in Algol systems is very far from unity, whereas in RS CVns it is generally close to unity; and mass transfer plays a major role in the evolution of Algol systems but is incidental in the evolution of RS CVns. The "BY Draconis" binaries are a separate class comprising close detached binaries consisting of main–sequence dwarfs, i.e., they differ from RS CVns because neither component is evolved. In each class, the crucial ingredient for activity seems to be the presence of a cool star with a convection zone in a binary system where corotation maintains rapid rotation. Not all close binaries containing cool stars show the same radio properties, however. The "Serpentids" are strongly interacting binaries superficially resembling Algols in that they consist of a hot and a cool star (typically B + K), but with with much greater mass transfer taking place. They and the similar "peculiar emission–line Algols" (Elias II & Güdel 1993; Güdel & Elias II 1996) are detected but are much weaker radio sources than are Algols (Elias II 1990), and may be thermal free–free emitters rather than nonthermal radio sources. Another related class is the W UMa binaries, consisting of two late–type (F to K) main–sequence stars in contact with one another and thus having the shortest possible binary periods (0.1 to 0.3 days) for systems consisting of non–degenerate stars. They are underactive in X–rays compared to other stars of similar spectral type in short–period binaries, and their radio luminosities are also much weaker than those of RS CVns (Hughes & McLean 1984; Beasley et al. 1993; Rucinski 1995), so the fact that the stars are in contact does seem to influence their activity levels.

Major VLA surveys of RS CVn systems have been carried out by Mutel & Lestrade (1985), Morris & Mutel (1988) and Drake et al. (1989,1992), while Algols have been surveyed by Umana et al. (1991,1998). At least 71 RS CVns and 17 Algols have been detected as radio sources by the VLA (Drake, Simon & Linsky 1992). They exhibit at least three types of radio emission (there is no obvious difference in the radio properties of the two types of binary):

1. *"Quiescent" emission* which is steady on a timescale of minutes but may be slowly modulated on a timescale of hours. This emission typically has a flat spectrum and is significantly circularly polarized (Mutel et al. 1987; White et al. 1990; Umana et al. 1993). It is attributed to gyrosynchrotron emision from a steady population of nonthermal electrons trapped in the corona of the cooler star. The flat spectrum comes from having a source which is optically thick, but with the size of the optically thick source increasing as frequency decreases. Brief examples of quiescent emission may be seen in Figure 7. VLBI measurements indicate that the size of the quiescent source can be larger than the stellar diameter, suggesting that the emission is not necessarily only associated with the cooler member of the system.

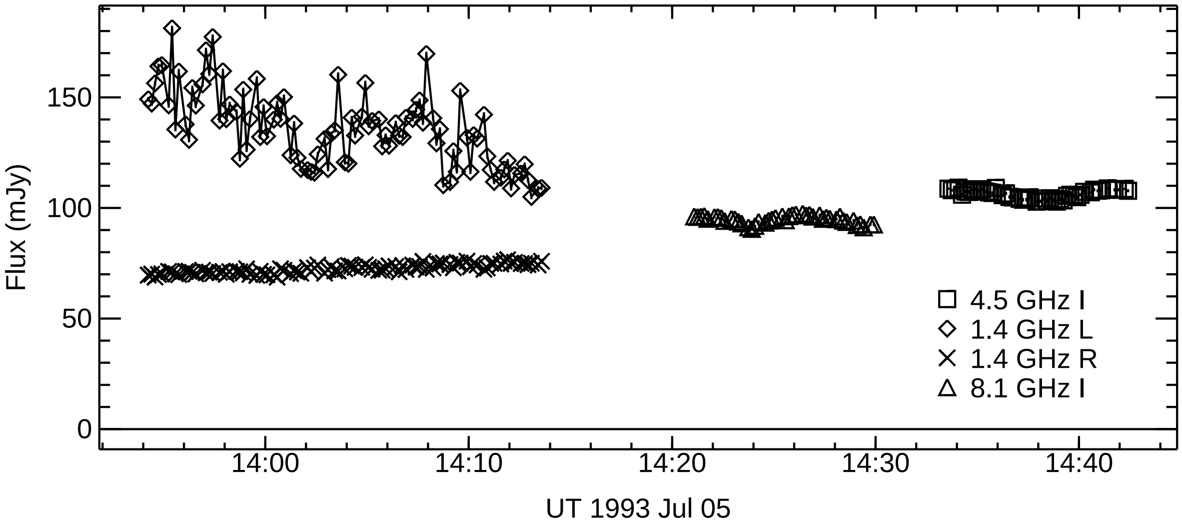

Figure 7. VLA observation of HR 1099 at 1.4, 4.5 and 8.1 GHz. At 1.4 GHz right (R) and left (L) circular polarizations are plotted separately, while at 4.5 and 8.1 GHz only the total intensity (Stokes I) as a function of time (10 s time resolution) is shown. At 1.4 GHz the left circular polarization shows a strong, highly polarized and rapidly fluctuating component which is attributed to coherent emission, present much of the time at low frequencies (White & Franciosini 1995). The 1.4 GHz R data and the 4.5 and 8.1 GHz data are representative of quiescent emission (albeit in a high state) from such systems.

2. *Radio outbursts*, in which the flux rises dramatically, the radio spectral index is positive and the degree of circular polarization is very small (e.g., Morris, Mutel & Su 1990). These are attributed to the impulsive acceleration of a large number of very energetic electrons which then form an optically thick synchrotron source of finite extent (possibly in the form of a plasmoid) which naturally has a rising spectrum. VLBI data suggest that as the radio outburst decays, the source expands (Trigilio, Umana & Migenes 1993). These flares are many orders of magnitude more luminous than solar microwave bursts, and represent the signature of an impressive energy release.

3. *Highly polarized coherent bursts* at low frequencies (e.g., Simon, Fekel & Gibson 1985; Lestrade et al. 1988; van den Oord & de Bruyn 1994; White & Franciosini 1995; Jones et al. 1996). At 1.5 GHz some form of this emission is often present when a star's quiescent flux is at a high level, and this fact led to some confusion regarding the natural sense of polarization at low frequencies. When the coherent emission is not very strong, it is difficult to recognize it as a phenomenon different from the quiescent emission, but because it is typically 100% polarized it dominates the observed polarization signal. The polarization of the coherent component is opposite to the polarization of the high–frequency quiescent emission, so for many years modellers tried to come up with gyrosynchrotron source geometries in which the sense of polarization reversed in going from high to low frequencies. In such models, it is very difficult to achieve degrees of polarization as high as those observed at 1.4 GHz. A natural explanation for the bursty coherent emission is that it is some form of plasma emission, common on the Sun at low frequencies. Plasma emission is polarized in the sense of the O mode, whereas gyrosynchrotron is polarized in the sense of the X mode. A striking example of this phenomenon is shown in Figure 7, where one sense of circular polarization at 1.4 GHz varies dramatically on a timescale

of seconds while the other remains steady. The VLA's sensitivity and ability to avoid source confusion made the identification of this separate component possible.

One might expect that rotational modulation would be a valuable tool in the study of the radio source in these binary systems, but there has been no evidence so far for rotational modulation or even eclipse of the radio emission in RS CVns or Algols. Partly this is due to the level of intrinsic variability in the radio flux, which tends to mask any repeated pattern, and partly this may be due to the difficulty of obtaining light curves over several periods of typically several days each. One binary system, V471 Tau, has shown radio eclipses when the white dwarf in the system passes behind the K dwarf, implying that the radio source is between the two stars and possibly tied to magnetic field lines connecting the two stars (Patterson, Caillault & Skillman 1993; Lim, White & Cully 1996).

I would be remiss if I failed to note that Barry carried out one of the first VLBI observations of a star (Algol), and succeeded in resolving it (Clark, Kellermann & Shaffer 1975)!

9. Cool main sequence stars

Figure 1 shows detections of main–sequence stars in all spectral classes from F down to M. The dramatic result of VLA observations of cool main–sequence stars is that they possess something unknown on the Sun: a nonthermal corona which produces strong and steady radio emission. That is, in addition to the thermal populations at 10^{6-7} K in stellar coronae which radiate X–rays, there are nonthermal populations of electrons, extending up to MeV energies, which are trapped on closed magnetic field lines and produce strong radio emission. There are several pieces of evidence for this conclusion: the radio spectra of the steady emission from active stars tend to be very flat even out to high frequencies, where thermal radio spectra would fall off rapidly with frequency; and the brightness temperatures of the radio emission, either measured directly by Very Long Baseline Interferometry (VLBI) which can resolve the sources, or inferred from observed flux levels using reasonable source sizes, are often in excess of 10^9 K. Such temperatures can only be produced by very energetic electrons unlikely to be in a thermal distribution. The fact that the radio emission is steady means that the corresponding population of gyrosynchrotron–emitting MeV–energy electrons is present continually in the corona. The Sun has no counterpart to this population: such nonthermal electrons are only present in the Sun's corona for very short periods during flares. This marks a fundamental difference between the coronae of active stars and the solar corona, a discovery made possible by the VLA's sensitivity.

The radio emission of M dwarfs was detected fairly early in the history of the VLA, as noted earlier, and there have been several surveys since (e.g., Linsky & Gary 1983; Willson, Lang & Foster 1988; White, Jackson & Kundu 1989; Güdel et al. 1993). Radio emission of main–sequence dwarfs in classes F–K was largely unknown (e.g., Drake et al. 1991) until the realization that X–ray luminosity could be used to select the stars most likely to be radio sources, and this led to systematic surveys of X–ray–selected stars in these spectral classes by M. Güdel and his collaborators (Güdel 1992; Güdel, Schmitt & Benz 1994; Güdel, Schmitt & Benz 1995; Güdel, Guinan & Skinner 1997), which have detected a number of stars at luminosities as high as 10^{15} ergs s^{-1} Hz^{-1} (although generally microwave fluxes are weak, below 1 mJy). It follows that the stars most likely to be detected are those which are observed to be extremely active at all wavelengths. Such high activity is well correlated with rotation and therefore also with youth, since it is believed that magnetic activity leads to the spin–down of main–sequence stars as they age. But not all the detected stars belong to this most active class: as the VLA ages, it has become possible to obtain long observations of faint stars which were not feasible in earlier years. Drake, Simon & Brown (1993) observed the inactive nearby F5 IV-V star Procyon on 5 occasions and, in 4 cases, observed flux levels ($\sim 33\mu$Jy; $L_R \sim 10^{11.7}$ ergs s^{-1} Hz^{-1}) consistent with optically thick emission from a 2 $\times 10^4$ K chromosphere plus a weak optically–thin coronal contribution from the known X–ray–emitting material in the corona. A similar long observation of the nearby A7 IV-V star Altair (Rucinski 1990) failed to detect it with a luminosity upper limit of 6×10^{12} ergs s^{-1} Hz^{-1}; ordinary A stars remain undetected as radio sources (Brown et al. 1990).

Active F to M dwarfs show the same sorts of radio activity exhibited by RS CVns: steady quiescent emission with a fairly flat spectrum (e.g., Güdel & Benz 1989; White, Kundu & Jackson 1989; Güdel 1994; Lim 1993), usually unpolarized or very weakly polarized (less so than for RS CVns); highly polarized coherent bursts at low frequencies (Gary, Linsky & Dulk 1982; Lang & Willson 1986; White, Kundu & Jackson 1986; Jackson, Kundu & White 1987; Kundu et al. 1988); and impulsive microwave flares at higher frequencies which look quite similar to solar flares (e.g., Rodonò et al. 1989; Güdel, Schmitt & Benz 1995; Lim & White 1995). Quiescent luminosities scale with the sizes of the stars: from 10^{12} ergs s^{-1} Hz^{-1} for M dwarfs up to 10^{15} ergs s^{-1} Hz^{-1} for F stars. One study of coherent bursts made novel use of the VLA's correlator to turn the spectral line system into a device to look at the dynamic spectrum of an electron beam passing through a stellar atmosphere, as is commonly done in solar radioastronomy (Bastian & Bookbinder 1987).

As noted above, recent detections of single stars amongst classes not previously known to be radio sources have been based on X–ray–selected samples which have become more readily available now through the *ROSAT* all–sky survey. The success of these surveys in making radio detections can readily be understood in general terms: both the X–rays, a result of coronal heating, and the radio emission, a diagnostic of nonthermal accelerated electrons, are the result of the free energy available from stellar activity. However, the relationship appears to be even more specific than this (Güdel et al. 1993; Güdel & Benz 1993). As demonstrated by Figure 8, which shows X–ray versus radio luminosity for stars covering a wide range of spectral types, the two are approximately proportional, with some notable qualifications, over about 5 orders of magnitude, and even solar flares appear to obey the same relationship: $\log L_R = \log L_X - 15.5$ (both in cgs units). The spread about this relationship is generally about 0.3 in the log. When simultaneously–measured radio and X–ray luminosities are compared, the relationship is even tighter (Benz & Güdel 1994). The exceptions to this relationship so far nearly all fall on the side of being more radio–luminous: the active subgiant binaries (RS CVns and Algols), the WTT stars, and some M dwarfs (notably UV Ceti and Rst 137B). The long–period binary Capella (G0III + G5III) is radio underluminous (Drake & Linsky 1986).

The good correlation evident in Figure 8 is puzzling because one can think of so many ways in which it might be destroyed. One of the most obvious is the well–established fact that the radio luminosity of a star is a much more variable quantity than is the X–ray luminosity. UV Ceti is one of the least–variable steady radio sources, but even it varies by about a factor of 3 (Güdel 1994), and it is very difficult to define a quiescent level for RS CVns (Drake, Simon & Linsky 1989), whereas a number of studies have shown that, when flares are discarded, the X–ray luminosity of active stars tends to be remarkably stable on timescales ranging from days to years, varying typically by less than 50% (e.g., Pallavicini, Tagliaferri & Stella 1990a; Stern, Schmitt & Kahabka 1995). The Sun's X–ray luminosity

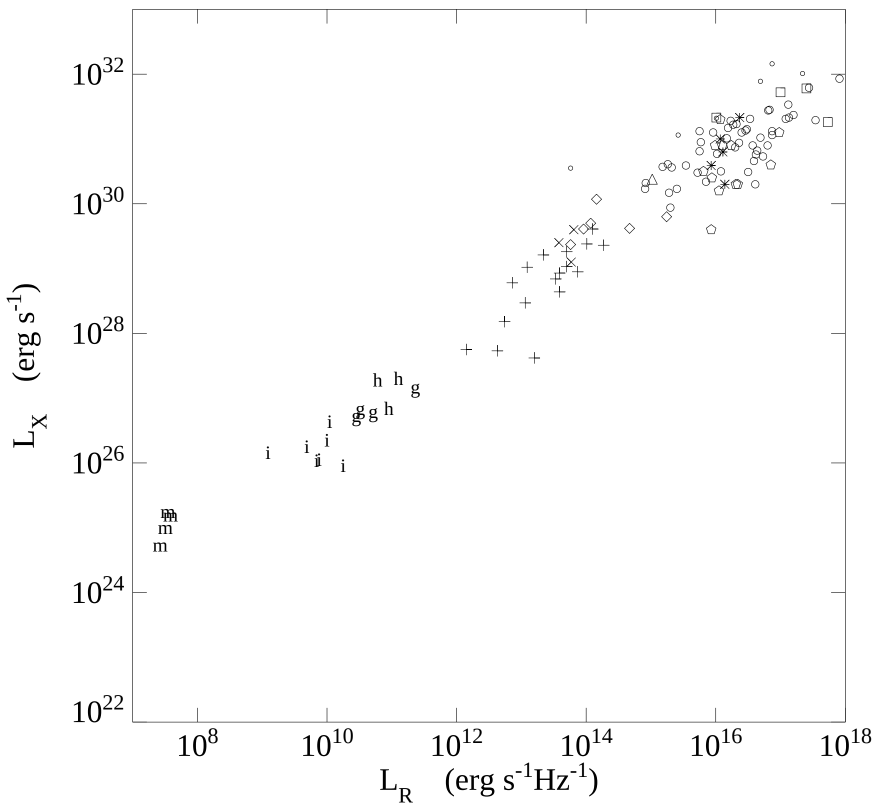

Figure 8. Comparison of soft X–ray and radio luminosities for several classes of stars (+, dMe's; ×, dK(e)'s; ⋄, BY Dra binaries; ◯, RS CVn binaries; ∘, RS CVn binaries containing two subgiants; △, AB Dor; ∗, Algol binaries; squares, FK Com stars; pentagons, WTT stars) and for solar flares of varying sizes (letters: m, solar microflares; i, impulsive solar flares of intermediate size; h, gradual solar flares with large impulsive phase; g, pure gradual events). From Güdel (1994).

varies by orders of magnitude over the solar cycle. Another curious feature of Fig. 8 is that it mixes radio luminosities at different frequencies. This will affect the correlation unless all the radio spectra are approximately flat, which is fortuitously the case.

Some of the correlation is no doubt due just to the scaling of coronal volume over the range of stellar types. If we assume that soft X–ray emission is the main energy loss mechanism for the stellar corona, and that the radio emission is optically thin, it may be shown that the condition $L_R \propto L_X$ requires that the parameter $B^n\tau$ be the same over a wide range of stellar classes and stellar sizes, where B is a magnetic field characteristic of the radio source, $n \approx 2.5$ and τ is some mean lifetime of a nonthermal electron in the corona (Güdel & Benz 1993; White 1996). If the radio emission is optically thick, which may well be the case at the commonly used frequency of 5 GHz, then there is no simple relationship between L_R and L_X.

10. Cool giant stars

As described earlier, single cool giant stars by and large lack the characteristics which make other stars radio–bright: they are cool enough to have convection zones but usually rotate too slowly to generate via a dynamo the sort of magnetic activity which makes young cool dwarfs and rapidly rotating subgiants such strong nonthermal radio emitters; and they have massive outflows, but the coolest of these giants have no source of ultraviolet photons which can ionize the outflow and make it visible via its free–free emission. What some of these stars do have are large photospheres.

A number of surveys of different classes of cool giant have been carried out, mostly by Steve Drake and collaborators: a survey of nearby G0 – M5 giants and supergiants detected 4 K and M giants (Drake & Linsky 1986) but none of the G giants with coronae; none of the coolest 22 M and C giants surveyed by Drake et al. (1087) were detected; none out of nine S–type red giants were detected by Drake, Hollis & Brown (1991); while Drake et al. (1991) detected 3 out of 16 F – M giants and supergiants, including IRC +10216, previously detected by Sahai et al.(1989); and Luttermoser & Brown (1992) failed to detect any of 7 N–type carbon stars. There is some overlap with planetary nebulae in this area of research: Knapp et al. (1995) observed 21 evolved stars in order to look for newly formed compact planetary nebulae, which might be detected as strong free–free sources since the new hot star can ionize the dense circumstellar shell left by the cool giant: they detected several sources.

FK Comae stars are also formally single cool giants, but their properties are suspiciously similar to those of the active close binaries: their spectral types are those of G2 – K2 giants, and they have rapid rotation. FK Comae itself has a rotation period of just 2.4 days, while the other possible members of the class have periods of up to 200 days. They show lightcurve modulations suggestive of starspots and very strong X–ray and chromospheric activity. It is speculated that they are actually coalesced W UMa binaries, with the cores of the two stars now inside a common envelope. Their activity extends to their radio emission: like RS CVns, they are very strong nonthermal radio sources. About 60 stars in this class have been identified (they are generally hundreds of parsecs away) and about a dozen have now been detected by the VLA (Hughes & McLean 1987; Drake, Walter & Florkowski 1990; Rucinski 1991; Skinner 1991; Drake, Simon & Florkowski 1999). The southern FK Comae star HD 32918 = YY Men may hold the record for the largest recorded radio luminosity of any of the nonthermal active stellar sources, during a flare which reached 10^{20} ergs s^{-1} Hz^{-1} (Slee et al. 1987).

In the case of some cool giant stars, such as IRC +10216 (Knapp et al. 1994), the radio continuum emission may be produced by dust which has formed in the cool dense envelope. Drake & Linsky (1986) argue that the emission from the K III giants they detected is from an ionized wind. For the M supergiants, the emission is apparently dominated by the stellar disk. In the Introduction I noted that the sole specific mention of stars in the science proposal for the VLA was a reference to "stellar envelopes", inspired by a paper by Weymann & Chapman (1965) entitled "On the possibility of detecting stellar coronas at radio frequencies". This was an estimate of the radio flux of Betelgeuse based on the assumption that it possesses a dense wind at a coronal temperature of order 10^5 K, but with an ionization boundary at 8.5 stellar radii. This paper correctly calculates the photospheric contribution to the radio flux (from a disk of size 44 milliarcseconds at a temperature of 3150 K), but strongly overestimates the contribution of the "corona" or ionized wind, which turns out not to exist for M supergiants like Betelgeuse.

Since the stellar photosphere is a source of (roughly) fixed temperature and size, its radio flux increases with the square of the frequency, and resolution improves directly with increasing frequency, so that higher–frequency observations are very attractive for these sources. In principle the VLA can resolve the size of many M supergiants in A configuration. However, at higher frequencies the atmosphere becomes a serious impediment to such measurements,

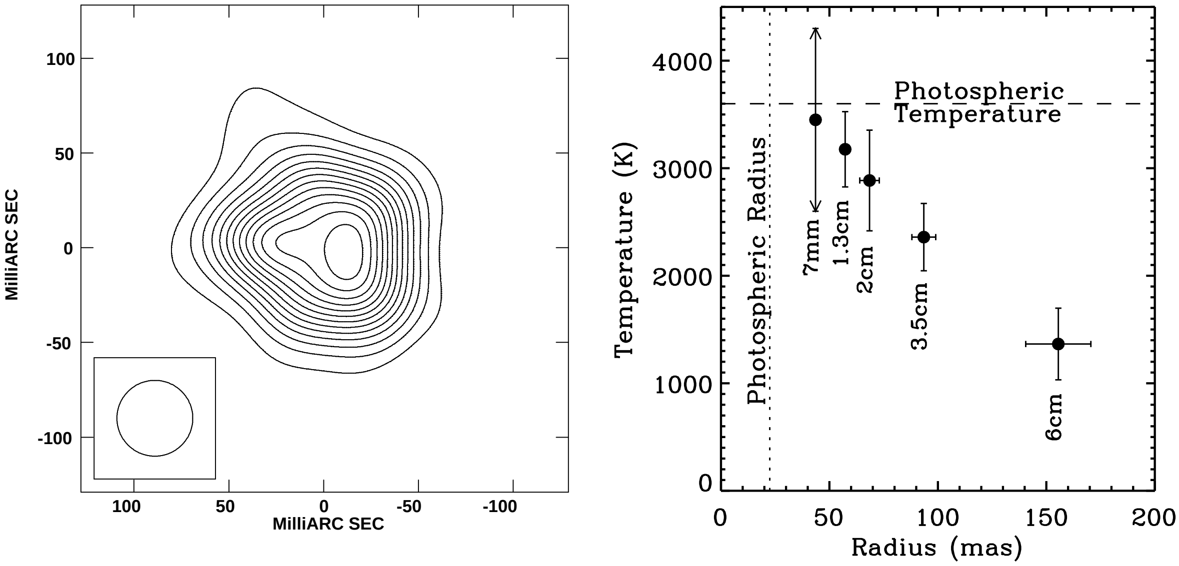

Figure 9. (left) VLA 43 GHz image of Betelgeuse. The resolution is 40 milliarcseconds and the contour interval is 250 K (in brightness temperature). The peak temperature on the disk is 3450 K, which is consistent with the photospheric temperature of 3600 K. (right) The variation of temperature in the atmosphere with radius, determined from the VLA observations of Betelgeuse at different frequencies which resolve the source size (Lim et al. 1998).

introducing phase errors which smear out the typically weak flux from these stars. In a technical tour–de–force, Reid & Menten (1997) overcame this problem in a study of long–period Mira variables by using strong H_2O masers in the atmospheres of the stars: they put the maser lines in one sideband and self–calibrated them to determine atmospheric phase corrections which they then applied to the continuum data in the other sideband. This yielded a source size of 0.08″ for W Hya at 22 GHz.

With the addition of 7 mm receivers to the VLA, it has become possible to do better than just measure source size: we can now actually map the "surface" of a star other than the Sun with several resolution elements across the disk (for red supergiants the concept of a surface barely applies: their outer atmospheres are very puffy, with enormous scale heights, making them quite different from a main–sequence star such as the Sun). Figure 9 shows the VLA 43 GHz image of Betelgeuse (Lim et al. 1998), which has an optical disk size of 45 milliarcseconds. A hot spot is seen on the west side of the disk. At 43 GHz the radio disk has a size of 90 milliarcseconds, and the size increases as frequency decreases (Figure 9). Since the flux and disk size can be measured with the VLA at a range of frequencies, the dependence of temperature on radius in the extended atmosphere can be determined, allowing atmospheric models to be tested directly.

11. The Sun

We close this review with a brief discussion of VLA observations of the Sun. This topic could take up a whole additional chapter, but since it is a star and not covered elsewhere in this volume, the Sun deserves a mention here. The Sun is simultaneously an excellent and a difficult target for the VLA. Its is strong and close, making it possible to resolve small structures in the atmosphere. However, it violates all the assumptions of aperture synthesis: it

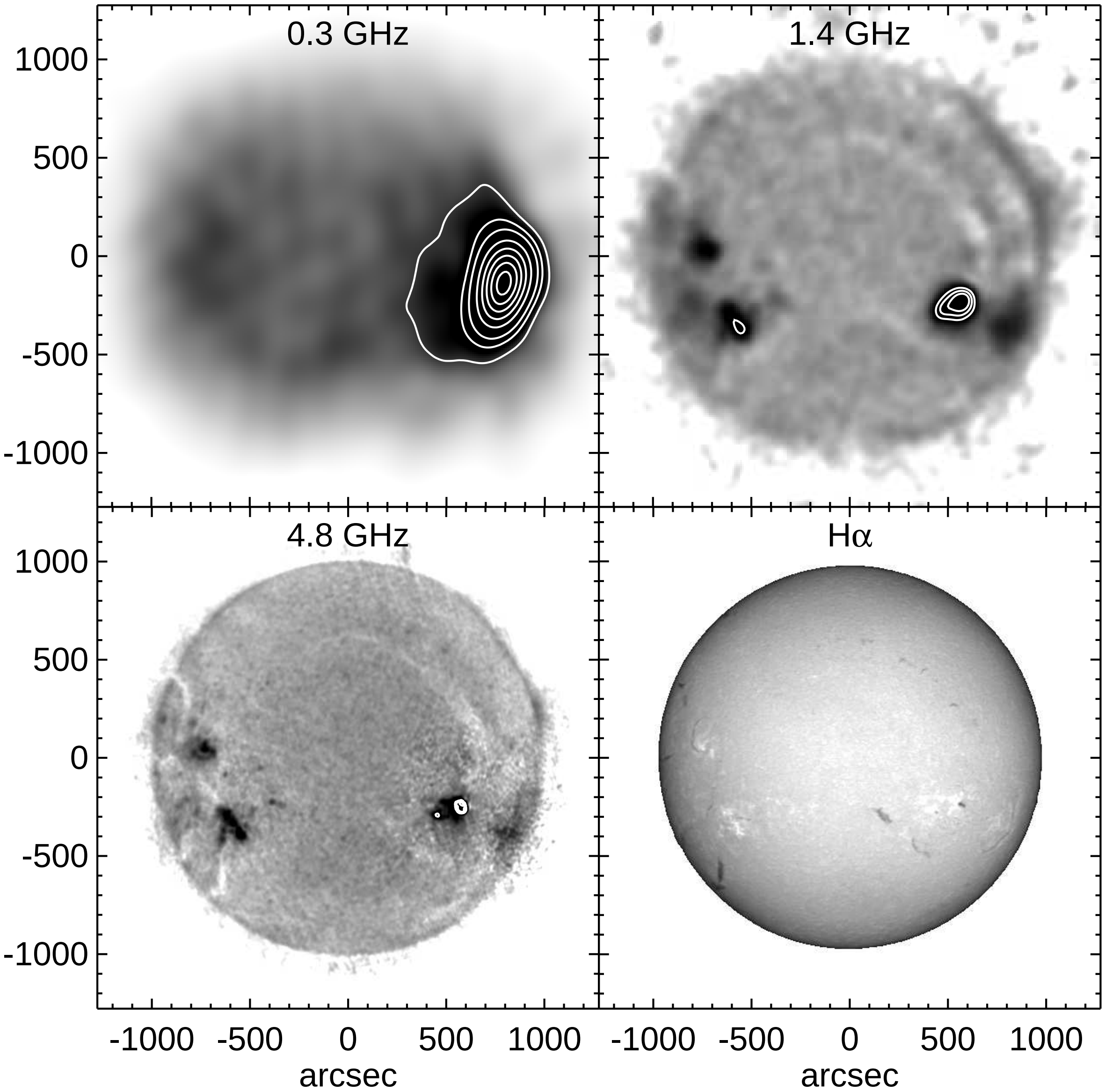

Figure 10. VLA images of the whole Sun on 1993 November 7 at three different radio frequencies, compared with an Hα image from Big Bear Solar Observatory. The 4.8 GHz image is a 26–field mosaic; both the 4.8 and 1.4 GHz images are maximum entropy deconvolutions using a disk as a starting model. The data were taken in "D" configuration: the spatial resolution is $220''$ at 0.3 GHz, $50''$ at 1.4 GHz and $12''$ at 4.8 GHz. White contours highlighting the brightest features are plotted at brightness temperatures of 0.8, 1.2, 1.6, 2.4, 3.2, 4.0, 4.8 and 5.6 $\times$ 10^6 K. The color table saturates (is black) at 0.8 $\times$ 10^6 K at 0.3 GHz, 0.6 $\times$ 10^6 K at 1.4 GHz and 0.1 $\times$ 10^6 K at 4.8 GHz. Solar west is to the right.

has flux on all spatial scales from $< 1''$ to the solar diameter of $\sim 2000''$, and its radio emission varies on all possible timescales, from sub–second fluctuations in flares and low–frequency radio bursts through variations on timescales of hours, such as active region evolution, out to variations on solar cycle scales. Nonetheless the VLA is still the preferred telescope for solar microwave studies for reasons of instantaneous snapshot uv coverage, resolution, sensitivity,

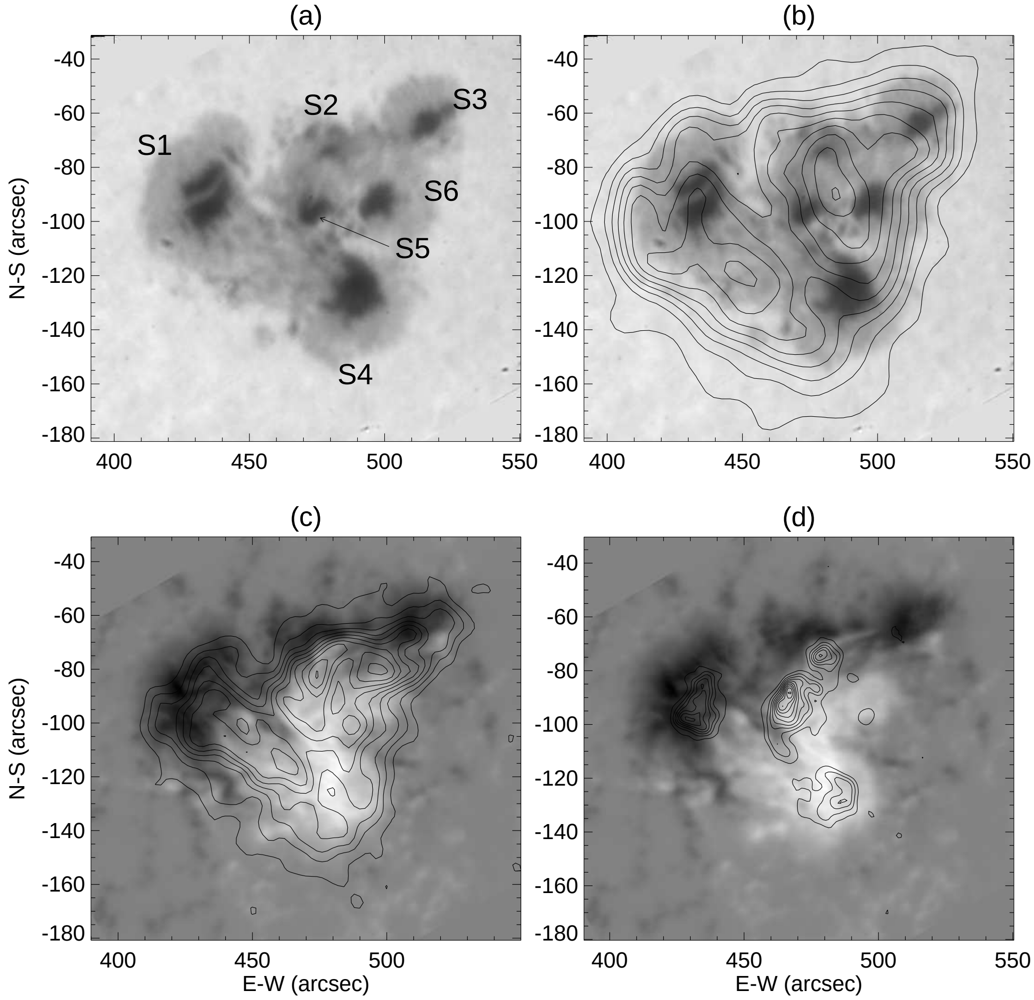

Figure 11. VLA observations of a complex solar active region reflecting the magnetic field and temperature distribution in the corona over the active region. The white–light image (a) shows a number of spots within the same penumbra. In panel (b) contours of the VLA 5 GHz emission are overlaid on the white–light image: since the radio emission is due to the gyroresonance process, the radio image corresponds to the electron temperature distribution on the surface in the corona where the magnetic field B equals 450 gauss. Panels (c) and (d) show contours of the 8.4 GHz (B = 750 gauss) and 15 GHz emission (B = 1350 gauss), respectively, overlaid on a longitudinal photospheric magnetogram which indicates the direction of the magnetic field at the surface (white = upgoing, black = downgoing field). The maximum brightness temperatures in the radio images are 4.4×10^6 K at 4.9 GHz, 4.6×10^6 K at 8.4 GHz, and 1.8×10^6 at 15 GHz, respectively. Contours begin at 10% of the maximum brightness temperature and then are 10% apart. From Lee et al. (1997).

frequency coverage and the fact that the primary beam includes the whole Sun at 20 cm wavelength.

Radio observations can be used to study virtually all phenomena in the solar atmosphere. Thanks to the properties of the main sources of radio opacity, bremsstrahlung and gyroresonance opacity, different radio frequencies can be used to probe different levels of the atmosphere. This is illustrated in Figure 10, which shows VLA images of the full Sun at three different frequencies together with an optical image. Low frequencies (< 1 GHz) are optically thick high in the corona along all lines of sight, so that the whole disk is at a brightness temperature of order 10^6 K. At these frequencies one also observes many examples of high brightness–temperature, coherent plasma emission from energetic electrons both during flares and at non–flare times as well. At frequencies between 1 and 3 GHz the quiet corona is optically thin and one sees down below the transition region except over active regions, where high–density, hot, X–ray–emitting plasma makes the corona optically thick to thermal bremsstrahlung. At these frequencies images need large dynamic range to map both the features at coronal brightness temperatures (10^6 K) and those at chromospheric temperatures ($\sim 10^4$ K). At yet higher microwave frequencies, the only regions of the corona to remain optically thick are regions of high magnetic fields (> 400 gauss) where gyroresonance opacity is strong: radio observations provide the only means for studying the magnetic field properties of the solar corona (e.g., Figure 11). This is an important topic since magnetic fields are believed to be involved in virtually all the major unsolved problems of the solar atmosphere: heating of the corona and chromosphere, solar flares, and active region formation. The VLA has and will continue to make important progress in our understanding of coronal magnetic fields (e.g., White & Kundu 1997).

At frequencies above about 20 GHz there are no regions of the corona which are optically thick (except possibly during the largest of all flares, which can increase the coronal emission measure by many orders of magnitude). Radio wavelengths penetrate into the chromosphere, where temperature contrasts are much smaller than in the corona. Here the value of VLA observations lies both in the spatial resolution achieved as well as in the fact that radio data provide a direct measurement of electron temperatures, whereas optical and ultraviolet observations must be compared with non–LTE radiative transfer calculations in order to make quantitative use of them.

Excellent snapshot *uv* coverage makes the VLA suitable for mapping phenomena variable on timescales from 0.1 seconds (using the high time resolution processor) upwards. The studies of flares and transient phenomena such as coronal loop brightenings, tiny flashes in the network of weak magnetic fields driven by solar convection and small coherent bursts have all benefited from the power of the VLA.

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Solar and stellar radio astronomers are a demanding bunch for a telescope scheduler: we are always trying to coordinate VLA observations with some X–ray satellite or other, or with some ground–based observatory with an impossible schedule, and sending Barry e–mails at the last minute with desperate requests for a change. Barry has put up with these demands for many years and although we don't always get what we would like, as long as other commitments permit it Barry has tried to schedule VLA time to make these multi–wavelength campaigns a success, including allocating system time when no other option was possible. We are all very grateful to Barry for his herculean scheduling work, as well as all the other features of the VLA which he had a hand in and which make it the world's premier radio telescope. I also thank Manuel Güdel for his advice on reddening corrections. Solar radio astronomy at the University of Maryland is supported by NSF grant ATM 96-12738 and NASA grants NAG 5-7901, 5-7232 and 5-6257.

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