Radio Emission from Cool Stars

Stephen M. White

Dept. of Astronomy, University of Maryland, College Park MD 20742

Abstract. Recent developments in the study of radio emission from cool stars are reviewed.

1. Stars as Radio Sources

The field of stellar radio astronomy would barely exist if active cool stars were similar to the Sun. However, many active stars appear to be fundamentally different from the Sun in that they possess 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.

Nonthermal coronae are widespread. Figure 1 shows an HR diagram for some of the stars detected as radio sources. A number of different classes of star are identified by the labels. The figure only includes systems for which V and $B-V$ measurements were readily available; in particular, it underrepresents the number of radio sources in close binaries (RS CVns and Algols) because separate measurements are not available for both components in most cases. Open symbols denote stars which probably do not possess nonthermal coronae in the sense defined above: these include luminous O stars, thought to be nonthermal radio sources due to energetic electrons accelerated in shocks in the massive, inhomogeneous stellar winds in these systems (e.g., White 1985), and the hot primaries in close binary systems. The magnetic Bp/Ap stars, on the other hand, do seem to possess nonthermal coronae. Some of the later–type M dwarfs have not been detected as steady radio sources but have shown radio flares.

Most of the stellar classes represented in Fig. 1 have been known to be strong radio sources for some years. However, radio emission of main–sequence dwarfs in classes F–K was largely unknown until the recent 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 1995b), which

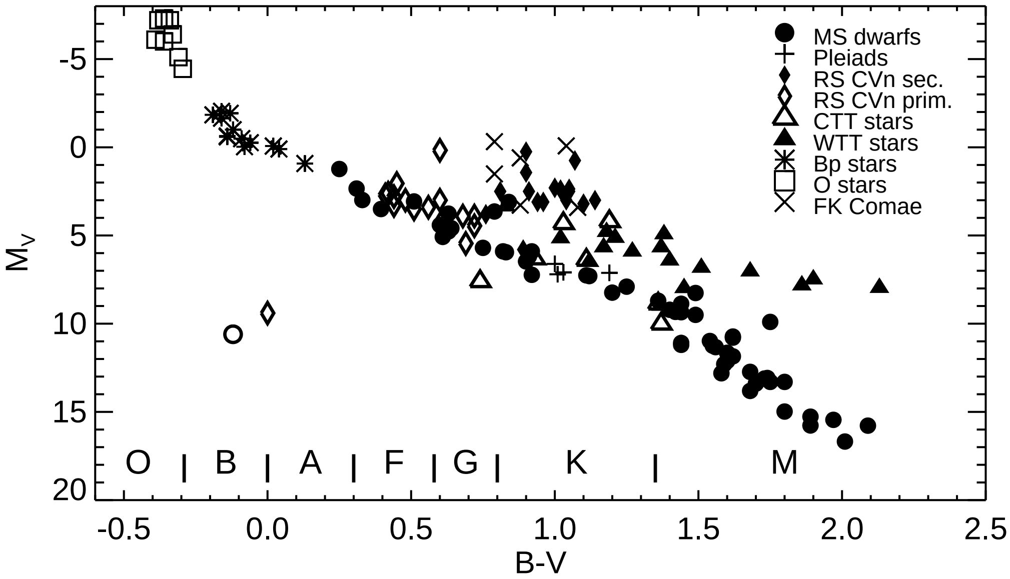

Figure 1. An HR diagram for stars detected as radio sources. Stars identified with closed symbols show evidence for the presence of nonthermal coronae, i.e., steady populations of nonthermal electrons trapped on closed magnetic field lines.

have detected a number of stars at luminosities as high as $10^{15.1}$ ergs s^{-1} Hz^{-1}, and often they appear to be young stars (e.g., Lim *et al.* 1992, Güdel, Schmitt & Benz 1995a, Güdel *et al.* 1995). Until recently there had also been a lack of detections in nearby young open clusters, which are important because they can be used to study the age dependence of stellar radio emission. However, Lim & White (1995) have now detected 3 rapidly–rotating G–K dwarfs in the Pleiades at luminosities of order $1-3 \times 10^{15}$ ergs s^{-1} Hz^{-1}.

Pre–main–sequence stars of ages $\sim 10^6$ yrs provide an interesting contrast. The weak–lined T Tauri (WTT) stars are strong nonthermal radio sources, 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 1992). The classical T Tauri (CTT) stars, which are of age similar to the WTTS but apparently less evolved in the sense that they still show strong evidence for circumstellar disks, accretion and strong molecular outflows associated with star formation (note that reddening corrections have not been applied to the CTT stars on Fig. 1, which accounts for their erratic distribution on the figure), have never shown any evidence for nonthermal emission. The few CTT stars which have been detected as continuum radio sources typically show spectra rising at microwave frequencies which suggest an origin as free-free emission from an ionized outflow, rather than nonthermal coronae. 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 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).

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. However, on the other occasion the star was 3–4 times brighter, indicating either a flare or else the presence of a bright discrete feature in the atmosphere. 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.

2. The Relationship between X–rays and Radio Emission

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 2, 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 good correlation evident in Figure 2 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 1990, Stern, Schmitt & Kahabka 1995). The Sun's X–ray luminosity varies by orders of magnitude over the solar cycle. Another curious feature of Fig. 2 is that it mixes radio luminosities at different frequencies. This

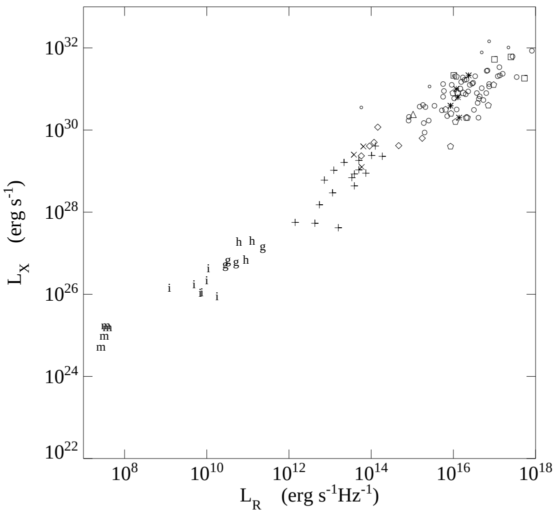

Figure 2. Comparison of soft X–ray and radio luminosities for several classes of stars (+, dMe's; ×, dK(e)'s; ⋄, BY Dra binaries; ○, RS CVn binaries; ∘, RS CVn binaries containing two subgiants; △, AB Dor; ∗, Algol binaries; squares, FK Com stars; pentagons, WTT stars) and for solar flares of varying 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).

will affect the correlation unless all the radio spectra are approximately flat, which is foruitously 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, then the X–ray luminosity $L_X \propto \dot{Q}_{th}$, where Q_{th} is the thermal energy content of the corona and $\dot{Q}_{th}$ is the coronal heating rate. It may be that all the coronal heating takes place initially as acceleration of nonthermal particles, which then deposit their energy in dense layers of the atmosphere and heat them to X–ray–emitting energies (as in solar flares), in which case $\dot{Q}_{th} \approx Q_{nth}/\tau$, where Q_{nth} is the energy density stored in nonthermal electrons and τ is some mean lifetime of a nonthermal electron in the corona. The radio emission can be optically thick or optically thin. The latter case requires a very hard electron energy distribution in order to produce the observed flat spectra: $E^{-\delta}$ with $\delta \sim 1.3$. It also requires that the spectral index remain flat out to high frequencies. In the optically–thin case, the gyrosynchrotron radio luminosity at a given frequency is roughly $\propto B^n Q_{nth}$, where B is the magnetic field and $n \approx 2.5$. (Actually $L_R \propto E_0^{1.2-0.90\delta}$ and $Q_{nth} \propto E_0^{1.0-\delta}$, where E_0 is the low–energy cutoff to the nonthermal electron energy distribution, so L_R is only very roughly $\propto Q_{nth}$.) If $Q_{nth} = \dot{Q}_{th}\tau$ and $L_X \propto \dot{Q}_{th}$, then $L_R \propto B^n \tau L_X$. If this equation is valid, then $L_R \propto L_X$, as in Fig. 2, implies that $B^n\tau$ is the same over a wide range of stellar classes, stellar sizes (the scale length will affect τ) and activity levels (a more careful version of this analyis is given by Güdel & Benz 1993). The relationship between L_R and L_X is less easily established if the radio emission is optically thick, which is the preferred explanation for the flat radio spectra: this requires that the optically–thick source size decrease rapidly as frequency increases, and above some turnover frequency where the whole source becomes optically thin, the spectrum should fall with increasing frequency. In this case $L_R \propto T_b A$, where T_b and A are the brightness temperature and optically–thick area, respectively, of the radio source. L_R is not very sensitive to $Q_{\rm nth}$ in this case because one does not see all the electrons in an optically–thick source. Thus if the radio emission at the typical observing frequencies is optically thick, there is no apparent simple theoretical relationship between L_R and L_X.

The interpretation of Fig. 2 remains unclear. Extensions to less–active stars will be valuable: if they should fail to satisfy the correlation, it may imply that the postulated saturation of activity indicators for the very active stars which make up Fig. 2 plays a role in the correlation.

3. Coronal Structure

Stellar radio emission arises in a stellar corona and we can use it to investigate coronal structure. An example where the thermal component of the corona can be addressed with radio data is discussed by White, Lim & Kundu (1994). They point out that the nearby active M dwarf stars are close enough that, if there are strong ($\sim$ 1000 G) magnetic fields permeating the lower corona as implied by magnetic field measurements of these stars, and if the hot ($\sim 10^7$ K) X–ray–emitting component of the corona detected in X–ray observations is cospatial with these strong fields, then the thermal gyroresonance emission from this hot coronal component should easily be detectable by the VLA at high frequencies (8 – 15 GHz), and should have the signature of a rising spectrum. Although such a spectrum has been seen on occasion (e.g., Cox & Gibson 1985, Güdel & Benz 1989), in general the stars are usually undetected at 15 GHz with upper limits well below the predicted levels. This means that the hot coronal component and the strong magnetic fields are not cospatial over a large fraction of the projected area of the stellar corona. This result is therefore consistent with the idea that the X–ray–emitting structures may be relatively compact, containing high densities, rather than covering the whole corona. If this is the case, then we expect to see rotational modulation of the X–ray emission as discrete structures rotate in and out of view.

As in X–ray studies, rotational modulation is an important diagnostic for radio work. That it takes place may most easily be seen in the case of the magnetic Bp stars, which are known from optical Zeeman measurements to have very strong ($\sim$ 10 kG) dipolar fields which may be offset from the rotational axis. Several of these stars are now known to show pronounced rotational modulation, consistent with emission by nonthermal electrons trapped in the coronal extensions of the surface fields (Leone & Umana 1993, Lim, White & Drake 1995, Lim, Linsky & Drake 1995). Among cool dwarf stars we have been less successful at finding rotational modulation, due in part to the intrinsic variability discussed above. A notable example is the K0 star AB Doradus. Lim et al. (1992,1994) find that it shows clear rotational modulation when the radio emission is strong, peaking at the same rotational phase over several months. However, the modulation is not evident when the emission is weak, suggesting that it is due to a discrete bright feature which is only occasionally present. On the other hand, the degree of modulation, when present, is very large and not easily modelled.

Another example of rotational modulation is displayed by V471 Tau. This is an eclipsing binary in the Hyades consisting of a K dwarf and a white dwarf in an 0.5–day binary orbit. Patterson et al. (1993) first reported evidence for an eclipse of the radio emission when the K dwarf obscures the white dwarf, and this has been confirmed by Lim, White & Cully (1995). The radio eclipse is about 0.3 orbital phases wide, whereas the optical eclipse is much shorter. The profile of the eclipse light curve suggests that the radio emission is dominated by a structure lying between the two stars, but probably anchored in the strong magnetic fields in the K dwarf corona and elongated towards the white dwarf. One of the interesting aspects of this observation is that it implies that either K dwarf activity is preferentially located on the side facing the white dwarf, which should then be a common feature of many close binaries, or else the radio emission may be associated with an interaction between the corona of the K dwarf and the magnetosphere of the white dwarf: the latter has a non–synchronous spin period of 9.25 min, so its magnetic field is whipping around inside the magnetosphere of the K dwarf, and the interface between the two could be the source of energy release.

Radio observations can also be valuable in the study of stellar activity cycles. One of the features of the solar cycle is the reversal in the sense of the dominant magnetic field in the two hemispheres of the Sun every 11 years. The orientation of the magnetic field in stellar spots can be determined from Zeeman Doppler imaging. It has been argued that by searching for reversals in these fields we can detect stellar cycles (e.g., Donati *et al.* 1992), for the few stars bright enough and rotating rapidly enough that the difficult technique of Zeeman Doppler imaging can be employed. Radio observations offer a simple complement to this approach, and the chance to extend the search to a broader range of stars. This is because many radio stars show a consistent sense of circular polarization in their emission over long timescales (years). The simplest interpretation is that the sense of circular polarization is determined by the orientation of the large–scale field, since we expect the small–scale fields to be highly variable on short timescales, and by following the history of the sense of polarization, we can look for reversals in the large–scale field. This simple technique can be applied to main–sequence dwarfs from F to M class, cool subgiants, and G–M pre–main–sequence stars, all of which show circular polarization. So far, no clear reversals have been reported. The two classes of stars for which we have the longest histories are G–K subgiants in RS CVn binaries ($\sim$ 20 yrs) and M dwarf flare stars ($\sim$ 15 yrs). The lack of radio polarization reversals implies that these typically rapidly–rotating and very active stars have cycles somewhat longer than 40 years.

4. Radio Flares

Stellar radio flares can be broadly divided into coherent and incoherent emissions. The former tend to be highly variable on short timescales, highly polar-

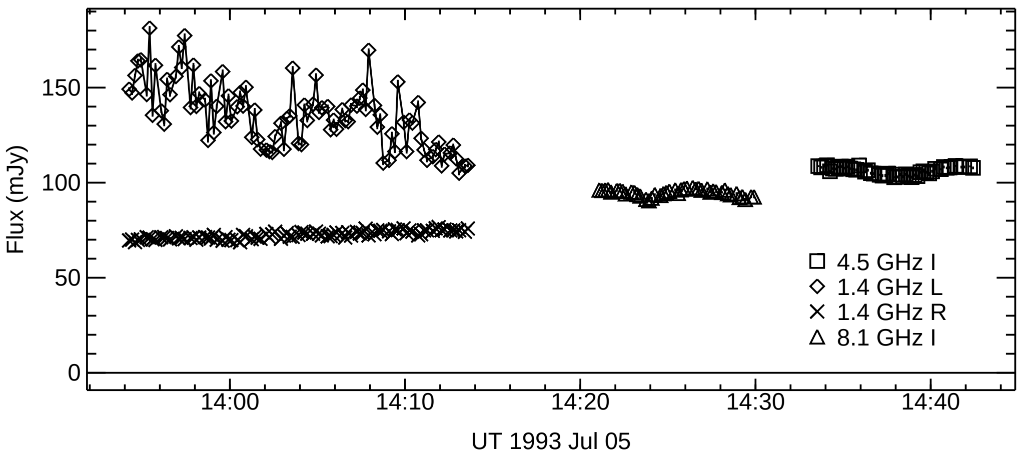

Figure 3. VLA observation of HR 1099 at 1.4, 4.5 and 8.1 GHz. At 1.4 GHz right (R) and left (L) circular polarizations are plotted separately, while at 4.5 and 8.1 GHz only the total intensity (Stokes I) as a function of time (10 s time resolution) is shown. At 1.4 GHz the left circular polarization 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).

ized, and confined to lower frequencies (mostly below 2 GHz). They are probably produced by mechanisms such as cyclotron maser emission or plasma emission, which produce exactly the high brightness temperature, highly–polarized emission observed. An example is shown in Figure 3. This example is important because it had been believed that RS CVn systems such as HR 1099 showed a polarization reversal in their quiescent emission as one moves from high to low frequencies, and this reversal was very difficult to explain with conventional gyrosynchrotron models. However, coherent emission such as that in Fig. 3 appears to be present at low frequencies much of the time, and it is polarized in the sense opposite to the polarization at higher frequencies, i.e., it is responsible for the reversed polarization at low frequencies once attributed to the quiescent component.

At higher frequencies, stellar radio flares become much more solar–like in their properties: moderate degrees of polarization, fast rise and slower decay, smoother time profiles and spectra peaked in the microwave range. However, they are orders of magnitude more luminous than their typical solar counterparts, and often display much longer timescales. Early attempts to find correlations with flares at other wavelengths were generally unsuccessful: radio flares tended to occur independently of optical or X–ray flares. However, this result is partly due to the fact that most of these studies used 1.5 and 5 GHz for the radio observations, and these frequencies suffer from two problems. The first occurs because at low frequencies the stellar corona will be optically thick at a great height over much of the star (just as for solar active regions), and flares taking place in the low corona may initially lie underneath the optically thick surface at these frequencies and be obscured. Secondly, the coherent emission discussed above is prevalent at the lower frequencies and acts as a source of confusion for correlation studies, since coherent emission requires very little energy and thus need not be associated with the stronger flares. More recent studies of correlations with other wavelengths have used higher frequencies, which penetrate deeper into the corona, and at these frequencies correlated events at different wavelengths are more common (e.g., Rodonò *et al.* 1989, Stern *et al.* 1992, Brown et al. 1996), although they remain sparse (e.g., Fox *et al.* 1994).

There are several valuable monitoring programs which use single–dish telescopes, on which extensive observing time is more readily available, to study the long–term radio behaviour of some of the brighter radio stars (mostly RS CVns; e.g., Umana *et al.* 1995). UX Arietis underwent a remarkable period of radio activity in the early 1990s, and there is a healthy debate among observers at the Bonn (Neidhöfer, Massi & Chiuderi-Drago 1993) and Noto (Trigilio, Leto & Umana 1995) telescopes and observers from NRL (Elias II *et al.* 1995) as to whether the timing of flares is correlated with orbital phase.

5. Very Long Baseline Interferometry

It was noted above that stellar radio flares often have timescales much longer than their solar counterparts, and this translates into the expectation that they may have much larger length scales also. VLBI can attain milliarcsecond spatial resolution and offers the possibility of actually resolving some of the larger radio structures on radio stars.

A simple but important use of VLBI is astrometry. Accurate radio position measurements fall out naturally from the observing technique used for radio interferometry, and they are made with respect to a stable extragalactic reference frame. One application is the measurement of proper motion and parallax for stars which are difficult to observe optically. Two recent examples are the active southern–hemisphere stars AB Doradus and HD 32918. AB Dor (K0) and its common–proper–motion M dwarf companion Rst 137B are amongst the most active nearby stars: their assumed distance of 25 pc put them above the main sequence and therefore they appeared to be very young stars. However, a VLBI measurement by Guirado et al. (1995) puts AB Dor at only 15 pc: this brings both stars much closer to the main sequence. HD 32918 (K1III) has long been believed to be an FK Comae star at 400 pc, but its activity levels are very high. The VLBI measurement confirms that this distance is correct. This makes HD 32918 perhaps the most luminous active radio star known, with a quiescent luminosity of order 10^{18} ergs s^{-1} Hz^{-1} and flares of up to 10^{20} ergs s^{-1} Hz^{-1} (Slee *et al.* 1987).

Another demonstration of the power of a simple VLBI measurement was given by Lestrade et al. (1993), who observed Algol (B8V + KIV) on four occasions carefully chosen to be the times when the projected separation of the stars on the sky was maximum. Due to the mass difference, the cooler star has a much larger projected orbital motion on the sky than the primary: 4 milliarcsec (mas) compared to 1 mas. The measured positions of the radio source show exactly the separation expected if the radio emission is centered on the K star, dramatically confirming the long–held assumption that most of the activity in Algol systems is associated with the secondary. VLBI has also shown that both components of the bright pre–main–sequence binary HD 283447 are radio sources, with a separation of 1.1 mas in agrement with the orbit inferred from spectroscopy (Phillips et al. 1996).

Radio flares have always been an important target for VLBI because strong fluxes are generally important for this technique, and the sources may be large enough to be resolved. In an observation of HR 1099 by Trigilio et al. (1993), the source size was observed to increase, and the brightness temperature decrease, as the radio flare decayed. This is consistent with a model in which a plasmoid containing nonthermal electrons is ejected by a flare and expands as it rises through the corona. Observations such as these have spurred modelling work to try to understand the physical properties of the radio sources as they evolve (e.g., Chiuderi Drago & Franciosini 1993, Franciosini & Chiuderi Drago1995). With experience and improvements in our understanding of the technique, VLBI is being extended to weaker and weaker objects, particularly with the use of phase–referencing (Lestrade *et al.* 1990), and is now routinely used for faint M dwarfs (e.g., Benz, Alef & Güdel 1995). With the advent of the Very Long Baseline Array (VLBA) and the standardizing of data analysis techniques, this technique will become more widely accessible to the community than at present, and we expect dramatic advances in this area in coming years. An example of how well we can now do for weak sources is given by Beasley & Bastian (this volume): they mapped the radio emission from UX Ari with the VLBA at one of the lowest flux levels ever observed from this star, and were able to map both a compact component and an extended component at flux levels so weak that imaging previously would never have been attempted.

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