The Solar–Stellar Connection

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Stars have proven to be surprisingly prolific radio sources and the added sensitivity of the Square Kilometer Array will lead to advances in many directions. This chapter discusses prospects for studying the physics of stellar atmospheres and stellar winds across the HR diagram.

1. Introduction

The discovery that radio emission from stars is quite common and readily detectable was one of the unexpected advances produced by the Very Large Array [35,11]. This discovery could not be predicted based on what we know of the Sun's radio emission, even though similar physical mechanisms are operating in stellar radio sources and so knowledge of the Sun's emission is essential for understanding stellar radio emission: this is the solar–stellar connection in radio astronomy. Most of the obvious classes of star have been surveyed, and many of them have been detected, including the expected thermal wind sources amongst both cool and hot mass–losing giant stars and symbiotic binaries, but also solar–like activity from magnetically active stars in the giant, subgiant, main–sequence and (more recently) brown dwarf classes, as well as in chemically peculiar B stars and pre–main–sequence stars. However, the total number of stars detected is still relatively small, and selection effects mean that in all cases we detect only the most luminous tail of the most nearby members of the populations of these objects, representing a strongly biassed sample. For no populations of stars do we have a complete radio sample, and particularly a completely detected sample, that can be used to study the relationship of radio emission, and by extension atmospheric structure, with other stellar properties such as evolutionary state.

Radio emission from stars comes from the atmosphere, and hence can be used to study the nature of the atmosphere. Two types of atmospheric emission are most common in the sources detected so far: emission from an extended outflowing envelope or wind, or emission from confined parts of the atmosphere such as the corona (where the temperature exceeds 10^6 K) or chromosphere (the lower transition region between the stellar photosphere and the hot corona, with temperatures in the range 5–20 $\times$ 10^3 K). Stellar outflows and chromospheres are generally detected via the mechanism known variously as *thermal free–free* or *bremsstrahlung* emission. This 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. Since the temperature of a stellar wind or a chromosphere is generally around 10^4 K, large radio fluxes require very large optically thick surface areas: a 1 milliarcsecond disk, which is the order of magnitude for the photosphere of nearby giant stars, with a brightness temperature of 10^4 K produces of order 1 microJy of radio flux at 10 GHz. For the currently detected objects, the source size is much larger than 1 milliarcsecond due to high densities or very low outflow speeds for the stellar winds, or very distended atmospheres in the case of supergiants such as Betelgeuse [20,16].

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. The brightness temperatures achieved by this mechanism can be much larger than with bremsstrahlung, since the radiating electrons have much more energy than a thermal electron in a 10^4 K wind. With magnetic field strengths of hundreds of gauss 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 upper SKA frequencies and the radio spectral index $-\alpha$ is then related to the nonthermal electron energy spectral index $-\delta$ by the synchrotron relationship $\alpha = (\delta - 1)/2$.

At low frequencies *plasma emission* is also important: this is a resonant process in which electrostatic Langmuir waves at the electron plasma frequency, $\nu_p = 9000\sqrt{n_e}$, are driven to very high effective brightness temperatures by coherent interaction with a beam or a loss–cone pitch–angle distribution and then convert to propagating transverse waves at ν_p or its harmonic, $2\nu_p$. Radiation at ν_p is heavily damped by collisional opacity and so this emission is typically seen only at low frequencies (i.e., low densities) or when the ambient plasma is very hot.

In this chapter, we will discuss likely advances in the field of stellar radio astronomy to be expected from SKA. No attempt will be made at a comprehensive review of previous results nor of priority: cited references are given as examples in which more detailed histories of the subject can be found. The chapter by Güdel in the collection "Science with the SKA", edited by A. R. Taylor and R. Braun, covers similar topics with a more organized review of previous results than is presented here, including an excellent discussion of the radio Hertzsprung–Russell diagram and SKA detection limits for stars.

2. Main–sequence Stars

At a distance of 1 AU, the quiet (non–flaring) Sun has a flux typically of order 3×10^6 Jy at 10 GHz, with the flaring Sun rising to 10 times this value during sporadic bursts that usually last tens of minutes or less. The quiet–Sun flux at 10 GHz is equivalent to a disk–averaged brightness temperature of order 20000 K [42], corresponding to the solar atmosphere becoming optically thick at this frequency in the chromosphere. At the distance of α Centauri, the nearest star (1.3 pc) and a close solar analog, these fluxes would be reduced to just 40 and 400 μJy, respectively (Figure 1). These numbers illustrate the fact that radio astronomy for truly solar–like stars is next to impossible with current instrumentation, but SKA's sensitivity will open a much larger range of "normal" main sequence stars for study at radio wavelengths. No main–sequence stars other than the Sun have been detected so far through their thermal atmospheres, although there have been specific searches [38,22], including α Cen; the only analogous detection is of weak emission from the F5 subgiant Procyon that is attributed to its chromosphere [7].

One of the important issues that a wider SKA survey will address is the source of stellar coronal activity. The dramatic result of VLA observations of cool main–sequence stars is that they possess something unknown on the Sun: a nonthermal corona that produces strong and steady radio emission. That is, in addition to the thermal populations at 10^{6-7} K in stellar coronae that radiate X–rays, there are nonthermal populations of electrons, extending up to MeV energies, that are trapped on closed magnetic field lines and produce strong radio emission. The Sun has no counterpart to this population: such nonthermal electrons are usually only present in the Sun's corona for very short periods during flares. There is some evidence for small populations of lower–energy long–lasting electrons in the Sun's outer corona, producing "storm" emission at meter wavelengths (probably via the plasma mechanism) that is unrelated to the flare radio bursts [17]. However, this seems to be very different from the process responsible for the nonthermal radio coronae in active stars.

The nature of these nonthermal coronae and their relationship to the thermal stellar atmosphere is poorly understood and will be an im-

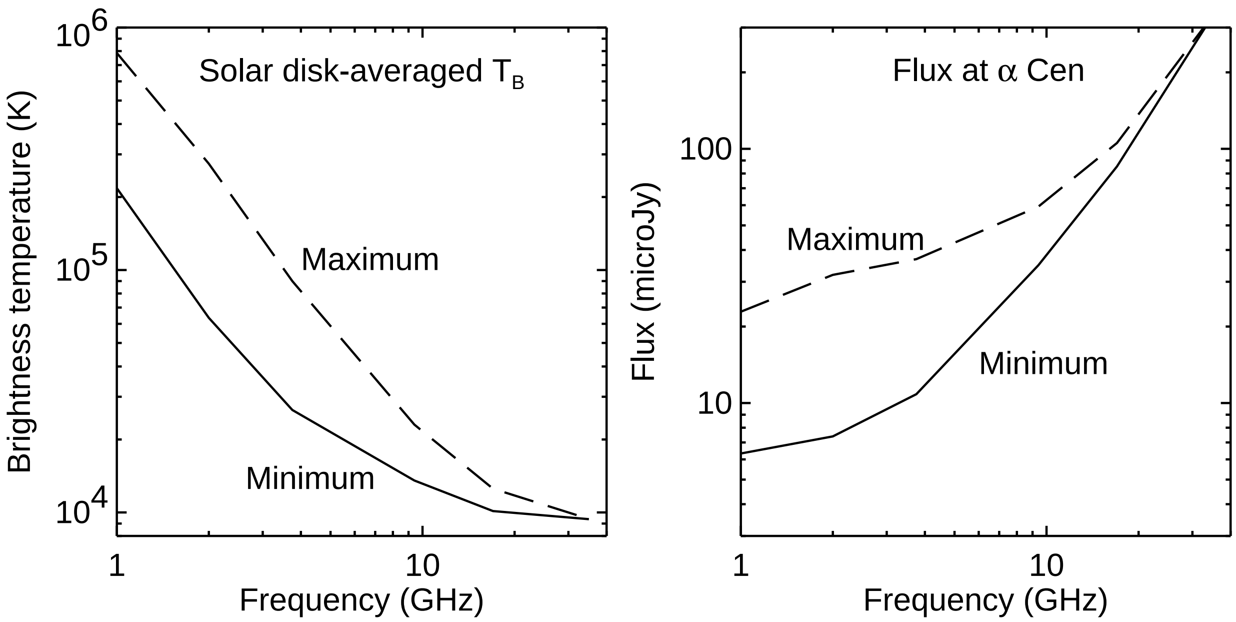

Figure 1. The quiet Sun as a star at the distance of α Cen. The left panel shows the disk–averaged brightness temperatures of the quiet (non–flaring) Sun as a function of frequency at solar minimum (solid line, May 1996) and solar maximum (dashed line, December 2001) using fluxes measured by the polarimeters of Nobeyama Radio Observatory. At right we show the same fluxes moved to the distance of α Cen, 1.3 pc, in units of μJy. VLA detection limts for α Cen would be around 30 μJy in 8 hours at 8 GHz if it were a northern–sky object, close to the predicted flux. In 8 hours of observing SKA will have a detection limit well below 1 μJy at 10 GHz: α Cen would be detectable out to 50 pc.

portant issue to be addressed by SKA. The stars that are presently detected with this emission are almost all young, rapidly–rotating stars active at other wavelengths, such as in X–rays, and generally have magnetic fluxes emerging through their photospheres that are many times the magnetic flux in the solar photosphere. The SKA will allow us to detect both the thermal atmospheres and, where present, the nonthermal atmospheres of a wide range of main–sequence stars. It should then be possible to determine the dependence of the nonthermal atmosphere on stellar mass, age, chemical composition and rotation rate. If we adopt a very conservative detection threshold of 0.5 μJy for SKA at 10 GHz (8 hour observation), then a solar–radius–sized chromosphere with a brightness temperature of 10^4 K is detectable out to a distance of 50 pc: since almost all stellar photospheres, except for those of white dwarves but including brown dwarves, are about this large or bigger, we can therefore expect a complete sample of detections of thermal atmospheres out to this distance from SKA, encompassing many thousands of stars.

For the nearby sources with sizes larger than a few milliarcseconds, including many red giants as well as a number of main sequence stars, spatially resolved SKA images at the upper end of SKA's frequency range, where fluxes are larger and the spatial resolution is better, will add important additional information to the modelling. Since only a few stellar atmospheres (really only Betelgeuse and Antares) can be imaged by existing radio telescopes, SKA will greatly expand the opportunities in this field.

In addition to the relationship between the nonthermal and thermal components of stellar atmospheres, the SKA will yield spectra of the thermal atmospheres that can be used to investigate the atmospheric structure. In the case of the Sun, the radio spectrum of the quiet atmosphere is dominated by the variation in temperature with height in the solar atmosphere, since the height of the layer optically thick in the radio decreases as the observing frequency increases. The bremsstrahlung mechanism is well understood, and hence the radio spectrum can be interpreted in terms of models of temperature and electron density versus height. These data are crucial for modelling stellar atmospheres because the radio data are taken in the Rayleigh–Jeans limit, and therefore the observed brightness temperatures are true temperatures. The radio data are used to constrain models based on UV line data which are difficult to interpret on their own because the UV lines are not formed in thermal equilibrium. The standard solar atmospheric models have been determined through a combination of UV and radio data [33,14], and the same approach will also be required for stellar modelling. With the large number of stars that SKA should detect, atmospheric models can be constructed across a wide range of stellar types.

Monitoring of the stars within 50 pc will also likely lead to the detection of stellar dynamo cycles in many main sequence stars. There is somewhat of an anomaly in the present data: active stars detected at X–rays do not show the order–of–magnitude modulation of the soft X–ray flux from the corona that the Sun exhibits over its 11 year cycle. However, since the stars we have good data for are mostly very active stars, it is believed that their cycles are expressed somewhat differently in the X–ray data. The quiet Sun also shows a clear cycle in its radio flux. This is due to the presence at solar maximum of sunspot regions with dense hot plasma and strong magnetic fields that render the corona optically thick by bremsstrahlung at low frequencies and by the gyroresonance mechanism (the non–relativistic version of the gyrosynchrotron mechanism, operating typically at the third harmonic of the electron gyrofrequency $\nu_B = 2.8 \times 10^6 \, B_{\rm gauss}$ Hz) at higher microwave frequencies. This produces a significant area of optically thick emission above the active regions, at a brightness temperature of order 2×10^6 K, in addition to the bremsstrahlung from the solar disk at chromospheric temperatures (several $\times$ 10^4 K). The solar–cycle modulation is more pronounced at lower microwave frequencies (e.g., 3 GHz) because the optically thick area at coronal temperatures is larger than at higher frequencies (since the required magnetic field strength or density is smaller) and the disk flux is smaller: at 3.75 GHz the modulation is from 0.7 MJy at minimum to 2.0 MJy at maximum, while at 9.4 GHz it is from 2.6 MJy at minimum to 3.5 MJy at maximum (Fig. 1). We can expect to detect such cycles on stars within 50 pc more easily than can be achieved by optical telescopes.

Polarization offers another valuable diagnostic in the radio regime: in the case of the Sun, the active–region component of the emission from a given hemisphere is quite strongly circularly polarized due to the fact that the large leading spots in active regions, where the strongest magnetic fields typically reside, almost always have the same polarity in a given hemisphere over the 11 year cycle, reversing in sense of polarization at the change of cycle. While we likely will not be able to resolve the two hemispheres of cool dwarf stars with SKA, the random orientations of stellar rotation axes means that in most cases we will be viewing stars predominantly pole–on, and the emission will show the circular polarization appropriate to the hemisphere dominating the emission. Any reversals due to dynamo cycles should then be observable as reversals of the dominant polarization [36]. The combination of these two techniques could produce a much larger sample of dynamo measurements than we presently possess.

3. Young Stars

Pre–main–sequence objects in star–forming regions are actually one of the most common types of detected radio star: without having spent a lot of time on them, we know of at least fifty detected stars in Taurus [5,3,24] and several tens in

Orion [13,9]. Deep observations of star–forming regions almost always produce a large number of faint continuum sources, often cospatial with infra–red sources, that are almost certainly young stars [28,30,27]. Since most of the known regions of star formation are over 100 pc away, they are difficult to study with the VLA for reasons of sensitivity, but SKA will solve this problem and provide a census of such sources. The field of view of SKA will make it an efficient survey instrument for detecting embedded objects, and the centimeter detections will provide an additional dimension to millimeter surveys of these regions with ALMA, which will pick up primarily dusty disks.

Many of the stars detected in these regions show nonthermal radio emission similar to that of nearby flare stars and active binaries. However, there remain many other objects, particularly fainter sources, that do not fit this profile. In Orion, several other classes of source have been identified [12], including partially–ionized globules that are associated with "proplyds" (proto–planetary disks), and deeply embedded nonthermal objects. The sources of stellar outflows often are very weak continuum sources, attributed to gas partially ionized by shocks in the outflows [1,27]: see also Hoare (this volume). Classical T Tauri stars show weak microwave emission, but it has quite different characteristics from the nonthermal emission exhibited by the weak–lined T Tauri stars that dominate radio surveys of star–forming regions: they are believed to be coeval with classical T Tauris but no longer in possession of disks. The conventional explanation for the nonthermal emission in these young sources is magnetic activity driven by the rapid rotation of a recently contracted and highly convective star: while it is present, a protostellar disk controls and limits the spin of the star, which can increase rapidly once the disk is gone.

While we have detected many sources in star–forming regions, they are mostly very faint detections and this limits our understanding of the sources. Frequently they are only detected in the 5–8 GHz range and spectral information is then limited. SKA will completely change this situation, producing a complete census for many star–forming regions and allowing a greater understanding of the nature of these sources and investigation of the underlying physics.

4. Stellar Flares

In most respects, stellar radio flares so far detected from solar–like stars have resembled phenomena that we recognize from the Sun:

- At lower microwave frequencies we tend to see highly ($\sim$100%) circularly polarized flares with inferred brightness temperatures (assuming source sizes comparable to the stellar disk) in excess of 10^{10} K [29,19,32]. Such high brightness temperatures in combination with high polarization are not consistent with an incoherent mechanism such as synchrotron emission, so they are almost certainly due to a coherent process, and more likely plasma emission than electron cyclotron maser emission because the polarization of the low frequency flaring is opposite to that of the high frequency flaring. This is expected if the low frequency flaring is plasma emission but the high frequency flaring is synchrotron emission [37]. As is also true on the Sun, this coherent low–frequency emission need not be related to flares at other wavelengths: it represents electrons accelerated in the stellar corona by some unknown form of energy release that does not show up at optical or X–ray wavelengths.

- At higher microwave frequencies we see analogs of solar microwave bursts, mildly circularly polarized with a spectrum peaked at centimeter wavelengths and extending as a power law to higher frequencies, consistent with synchrotron emission from electrons of energies from hundreds of keV upwards. On the Sun, the microwave bursts are invariably associated with solar flares and X–ray bursts, with the implication that all the observed high–energy phenomena are due to electrons accelerated in the flare energy release. In active stars, the correlation between flaring at different wavelengths is not as strong: when the X–ray flare rate is high, so is the radio flare rate [2,10], and sometimes radio flares are seen in conjunction with X–ray flares, but frequently flares in both wavelength ranges occur within a given period but with no obvious connection linking them [15,25].

- VLBI observations have revealed another difference between solar radio bursts and stellar radio flares: the source sizes of stellar radio bursts grow with time and can reach values much larger than the stellar disk [31], whereas microwave flares on the Sun never achieve sizes significantly greater than the active region in which they occur. This suggests a mechanism in which the energy density of nonthermal particles in the radio source is so high that it behaves like a plasmoid (a self–contained volume of magnetic field entraining nonthermal particles) that evolves somewhat like a fireball.

There is one important problem with the "solar" interpretation of the higher-frequency stellar microwave flares given above: while the low–frequency spectrum is rising as expected for an optically thick synchrotron source, the high–frequency spectra of these events tend to be embarrassingly flat during the decay phase and are not consistent with the spectra expected of nonthermal distributions of electrons accelerated in flares. The spectrum of the quiescent (non–flaring) emission from active stars, also attributed to synchrotron emission, also shows these flat high–frequency spectra. The resolution of this problem is not clear. Some solar radio bursts have spectra that rise from low frequencies well into the millimeter domain [18], but these events are exceedingly rare.

SKA will clearly identify radio flare phenomena, presently unknown due to sensitivity limitations, across wide ranges of stellar types and allow comparison with solar–flare activity. SKA will be able to follow variations in flares on timescales an order of magnitude shorter than is presently possible, providing a much clearer picture of the underlying physics. This will permit us to understand the nature of energy releases in the atmospheres of stars of different masses and ages, and provide another important piece of the puzzle that is stellar behaviour. SKA will also have the sensitivity to make dynamic spectra of stellar flares, i.e., spectra as a function of time, that can reveal electron beams or other disturbances such as shocks propagating through the stellar coronae.

5. Stellar Winds

This topic is also covered in the chapters by Hoare and Marvel (this volume). Stellar winds come in many different guises. In hot stars, powerful line–driven winds carry a large momentum and can have a major effect on the stellar environment, blowing bubbles in the local medium and creating dense shells. Cool supergiants such as Betelgeuse have very slow outflows, thanks to the very low gravity (and hence escape velocity) at their distended photospheres. Main sequence stars like the Sun have relatively low–momentum winds, but with quite high velocities ($\sim$ 500 km/s). These winds are described as "coronal" winds because they are not radiatively driven like the winds of very luminous stars, but rather exist as a result of the pressure in the stellar atmosphere via Parker's mechanism.

Very little is actually known about the winds of other cool main sequence stars because they are weak and very difficult to measure with existing techniques: the best data come from absorption in the wings of the Lyman α line observed with HST [39,40], and they show winds with properties very similar to the Sun's (2×10^{-14} M$_\odot$ yr^{-1}) in α Cen (G2V) but much weaker in Proxima Cen (M5.5Ve). The radio emission from solar–like winds is weak. For a spherically symmetric, constant–velocity, fully–ionized coronal wind, we find

$$S \approx 1\ \mu\mathrm{Jy}\ (\frac{\nu}{10\ \mathrm{GHz}})^{0.6}\ (\frac{T}{10^6\ \mathrm{K}})^{0.1} (\frac{\dot{M}}{10^{-13}\ M_\odot\ \mathrm{yr}^{-1}})^{4/3} (\frac{v_\infty}{300\ \mathrm{km\ s}^{-1}})^{-4/3}\ d_{pc}^{-2}$$

where v_∞ is the terminal velocity of the wind, T the temperature of the wind, and d_{pc} the distance to the star in parsecs [26,41]. This suggests that winds an order of magnitude more powerful than the Sun's would be detectable by SKA at least for some nearby stars, opening the possibility of improving our knowledge of mass loss rates for cool main sequence stars. However, there is a simple argument that states that for any star in which we can see coronal radio emission, we cannot detect the wind at radio wavelengths because the wind detection relies on an optically thick surface in the wind. However, if we see coronal emission, then the wind must be optically thin [21]. Since so many nearby stars are detected via their coronal or chromospheric emission, this argues that essentially none of the cool low–luminosity stars have mass loss rates much exceeding the Sun's.

Two very different emission mechanisms are responsible for radio emission from hot star winds. Thermal free–free is responsible for the classic stellar–wind radio emission. As noted earlier, the opacity for this mechanism varies as $n_e^2\, T^{-1.5}\, \nu^{-2}$. 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.

In addition to the thermal wind emission, many sources also show nonthermal synchrotron emission. It is important in hot stars because of the facility with which shocks can form in the powerful 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 [23]. 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 has been developed [34]. 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 [4]. 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. There is currently a healthy debate as to whether nonthermal radio emission is only seen in binary systems [6], implying that it may be due to the colliding–winds scenario and that the single–wind model is ineffective.

Clearly SKA will detect many more winds from luminous stars than we presently know of and greatly expand the range of stellar types for which mass loss rates are known: for luminous stars the wind flux is

$$S \approx 70\ \mu\mathrm{Jy}\ (\frac{\nu}{10\ \mathrm{GHz}})^{0.6}\ (\frac{T}{10^4\ \mathrm{K}})^{0.1} (\frac{\dot{M}}{10^{-7}\ M_\odot\ \mathrm{yr}^{-1}})^{4/3} (\frac{v_\infty}{300\ \mathrm{km\ s}^{-1}})^{-4/3}\ d_{kpc}^{-2}$$

where d_{kpc} is the distance to the star in kiloparsecs. However, in this field, most work will involve collaboration with ALMA because the combined frequency range of the two instruments probes a wide range of radii within the wind and will be needed to investigate effects such as radius–dependent variations in the ionization fraction that are important in very dense winds. Observations of the spectrum are also needed to separate out the relative contributions of nonthermal emission with a falling spectrum and thermal wind emission with a rising spectrum.

Spatial resolution will also be very important for the study of stellar winds. The famous mass–losing B[e] star MWC 349 is an example of the surprises in store when we have sufficient spatial resolution: this star was the prototypical thermal stellar wind radio source whose $\nu^{0.6}$ spectrum was for many years regarded as perfectly explained by spherical stellar wind models. However, when the VLA finally resolved the star, it was found to be anything but spherical, showing at high resolution a curious edge–brightened polar outflow apparently associated with a dust disk [8]. Another example is the Wolf–Rayet binary system WR 140 (HD 193793), which shows both thermal and nonthermal components in the system simultaneously. However, with an orbit dimension of only 26 mas the system is too small for the VLA to resolve and despite being one of the brightest WR systems in the radio, it is barely strong enough to be observed successfully on long baselines with MERLIN or VLBI. The improvements in both sensitivity and spatial resolution afforded by SKA will allow us to study the spatial structure of the outflows of many more systems, both single and binary, and to understand their properties in a systematic fashion impossible with the few examples that we presently have.

REFERENCES

1. Anglada, G. 1995, Rev. Mexicana. Astron. Astrof. (Serie de Conferencias), 1, 67
2. Bower, G. C., Plambeck, R. L., Bolatto, A., McCrady, N., Graham, J. R., de Pater, I., Liu, M. C., & Baganoff, F. K. 2003, Astrophys. J., 598, 1140
3. Carkner, L., Mamajek, E., Feigelson, E., Neuhäuser, R., Wichmann, R., & Krautter, J. 1997, Astrophys. J., 490, 735
4. Chen, W. & White, R. L. 1994, Astrophys. Space Sci., 221, 259
5. Chiang, E., Phillips, R. B., & Lonsdale, C. J. 1996, Astron. J., 111, 355
6. Dougherty, S. M. & Williams, P. M. 2000, Mon. Not. Roy. Astron. Soc., 319, 1005
7. Drake, S. A., Simon, T., & Brown, A. 1993, Astrophys. J., 406, 247
8. Dreher, J. W. & Welch, W. J. 1983, Astron. J., 88, 1014
9. Felli, M., Taylor, G. B., Catarzi, M., Churchwell, E., & Kurtz, S. 1993, Astron. Astrophys. Supp. Ser., 101, 127
10. Furuya, R. S., Shinnaga, H., Nakanishi, K., Momose, M., & Saito, M. 2003, Publ. Astron. Soc. Japan, 55, L83
11. Güdel, M. 2002, Ann. Rev. Astron. Astrophys., 40, 217
12. Garay, G. 1987, Revista Mexicana de Astronomia y Astrofisica, 14, 489
13. Garay, G., Moran, J. M., & Reid, M. J. 1987, Astrophys. J., 314, 535
14. Gu, Y., Jefferies, J. T., Lindsey, C., & Avrett, E. H. 1997, Astrophys. J., 484, 960
15. Güdel, M., Benz, A. O., Schmitt, J. H. M. M., & Skinner, S. L. 1996, Astrophys. J., 471, 1002
16. Harper, G. M., Brown, A., & Lim, J. 2001, Astrophys. J., 551, 1073
17. Kai, K., Melrose, D. B., & Suzuki, S. 1985, in Solar Radiophysics, ed. D. J. McLean & N. R. Labrum (Cambridge: Cambridge University Press), 415
18. Kaufmann, P., Correia, E., Costa, J. E. R., Vaz, A. M. Z., & Dennis, B. R. 1985, Nature, 313, 380
19. Lestrade, J. F., Mutel, R. L., Preston, R. A., & Phillips, R. B. 1988, Astrophys. J., 328, 232
20. Lim, J., Carilli, C. L., White, S. M., Beasley, A. J., & Marson, R. G. 1998, Nature, 392, 575
21. Lim, J. & White, S. M. 1995, Astrophys. J., 453, 207
22. Lim, J., White, S. M., & Slee, O. B. 1996, Astrophys. J., 460, 976
23. Lucy, L. B. & White, R. L. 1980, Astrophys. J., 241, 300
24. Magazzù, A., Umana, G., & Martín, E. L. 1999, Astron. Astrophys., 346, 878
25. Osten, R. A., Brown, A., Ayres, T. R., Drake, S. A., Franciosini, E., Pallavicini, R., Tagliaferri, G., Stewart, R. T., Skinner, S. L., & Linsky, J. L. 2004, Astrophys. J. Supp., 153, 317
26. Panagia, N. & Felli, M. 1975, Astron. Astrophys., 39, 1
27. Reipurth, B., Rodríguez, L. F., Anglada, G., & Bally, J. 2004, Astron. J., 127, 1736
28. Rodríguez, L. F., Anglada, G., & Curiel, S. 1999, Astrophys. J. Supp., 125, 427
29. Simon, T., Fekel, F. C., & Gibson, D. M. 1985, Astrophys. J., 295, 153
30. Stine, P. C. & O'Neal, D. 1998, Astron. J., 116, 890

31. Trigilio, C., Umana, G., & Migenes, V. 1993, Mon. Not. Roy. Astron. Soc., 260, 903
32. van den Oord, G. H. J. & de Bruyn, A. G. 1994, Astron. Astrophys., 286, 181
33. Vernazza, J. E., Avrett, E. H., & Loeser, R. 1976, Astrophys. J. Supp., 30, 1
34. White, R. L. 1985, Astrophys. J., 289, 698
35. White, S. M. 2000, in Radio Interferometry: The Saga and the Science (NRAO Workshop 27), ed. D. G. Finley & W. M. Goss (Associated Universities, Inc.), 86
36. White, S. M. 2002, Astronomische Nachrichten, 323, 265
37. White, S. M. & Franciosini, E. 1995, Astrophys. J., 444, 342
38. White, S. M., Lim, J., & Kundu, M. R. 1994, Astrophys. J., 422, 293
39. Wood, B. E., Linsky, J. L., Müller, H., & Zank, G. P. 2001, Astrophys. J. (Lett.), 547, L49
40. Wood, B. E., Müller, H., Zank, G. P., & Linsky, J. L. 2002, Astrophys. J., 574, 412
41. Wright, A. E. & Barlow, M. J. 1975, Mon. Not. Roy. Astron. Soc., 170, 41
42. Zirin, H., Baumert, B. M., & Hurford, G. J. 1991, Astrophys. J., 370, 779