Millimeter Continuum Observations of Stars

Roberto Pallavicini[1] and Stephen M. White[2]

[1] Osservatorio Astronomico, Palazzo dei Normanni, I-90134 Palermo, Italy
[2] Department of Astronomy, University of Maryland, College Park, MD 20742, USA

Abstract. We review the scientific advances to be expected from millimeter continuum observations of stars by a Large Southern Array (LSA). We discuss briefly several topics including millimeter observations of the Sun, winds of hot stars, circumstellar disks of pre-main sequence stars, circumstellar shells and mass loss in cool giants, symbiotic stars, and non-thermal emission in active binaries, flare stars and accretion powered X-ray sources. We show that even in the more limited area of continuum observations, the proposed LSA will allow major advances in virtually all fields of stellar astronomy.

1 Introduction

Various papers at this conference have discussed millimeter radio emission for specific classes of stars which are either very young (protostars) or are in very late stages of evolution (AGB and post-AGB stars). These are objects in which a rich spectrum of molecular lines is observed and which are sufficiently extended to be spatially resolved in some cases with the presently available instrumentation (see Sargent and Welch 1993 for a review). In addition to these objects, there are many other stars (including the Sun) for which continuum observations will be very fruitful. Although more limited in scope, this type of observation provides essential clues to understand the physics of various classes of stellar objects, and constitutes a powerful addition to current studies of stars at centimeter and decimeter wavelengths. We will try to demonstrate that even in this more limited field a large millimeter array will provide major advances of which the present data give only some tantalizing hints.

2 Millimeter Emission from the Sun

Before discussing stars, it may be useful to summarize briefly a few basic facts of solar millimeter radiation. Although the proposed Large Southern Array may not be suitable for solar observations, the Sun remains the prototypical stellar object which can be observed in far more detail than any other star. Whereas solar microwave emission consists of various components originating in the corona (a quiescent component due to thermal free–free emission, an active component associated with magnetic active regions which is due mostly to thermal gyroresonance emission in strong magnetic fields, and a flare component which contains gyrosynchrotron emission at microwave frequencies, and coherent plasma emissions at decimetre- and metre-wavelengths; see, e.g. Dulk 1985), observations of the Sun at millimeter wavelengths (such as those currently carried out with the BIMA array) provide information quite different from that obtained at lower frequencies. Thermal gyroresonance and plasma emission are not relevant for millimeter continuum emission. Since radiation of increasingly shorter wavelengths originates from deeper and deeper layers in the solar atmosphere, such that at at $\lambda = 3$mm the emission comes not from the corona but from an optically–thick layer in the chromosphere at a temperature of ≈ 7000 K. At $\lambda =$ 1 mm most of the radiation comes from a somewhat deeper layer at ≈ 6000 K. Millimeter observations, therefore, provide a unique way to investigate the upper photosphere and low chromosphere of the Sun and stars; they have an advantage over UV and optical observations in that they measure the temperature of the ambient electrons directly. In flares, nonthermal gyrosynchrotron emission at millimeter wavelengths is produced by much higher energy electrons than are typically relevant at microwave frequencies. This is due to the fact that the peak frequency of the incoherent synchrotron emission scales as $\nu_{max} \sim \gamma^3\ \nu_B$ where γ is the Lorentz factor and $\nu_B \propto B$ is the cyclotron frequency. Since typically $\nu_B\ \sim 1$ GHz ($\nu_B\ < 10$ GHz everywhere) in the solar corona, emission in the millimeter range requires $\nu_{max} \gg \nu_B$, i.e., $\gamma \gg 1$. Thus the millimeter emisison is produced by MeV–energy electrons, whereas the microwave emission is typically produced by mildly relativistic electrons with energies of several hundred keV. Observations at millimeter wavelengths therefore provide a powerful diagnostic tool for high energy electrons in solar (and stellar) flares, complementary to that provided by γ-ray astronomy for nuclear particles. Extensive observations carried out at BIMA at 3.5mm (e.g. Lim et al. 1992, Kundu et al. 1994) have beautifully demonstrated this in the case of solar flares, and reveal differences in the production of the low and high energy electrons.

3 Millimeter Emission from Stars

We expect stars to produce millimeter continuum emission by three main mechanisms: thermal free-free, nonthermal gyrosynchrotron, and dust opacity. The most complete survey of millimeter emission from stars made up to now is that of Altenhoff, Thum and Wendker (1994) who have used the IRAM 30m single-dish telescope with the MPIfR bolometer at 250 GHz (1.2mm). 268 stars were surveyed, mostly with a flux at 5 GHz in excess of 1 mJy. 122 stars were detected at a limiting sensitivity of $\approx 10-30$ mJy. The spectral index from 5 to 250 GHz may be used to give some crude information on the emission mechanism. Altenhoff et al. have organized their sample in various subclasses which form a useful starting point, even though a given class may contain objects which differ drastically in their physical properties. They include:

- O - B stars with fluxes at 250 GHz from $10 - 150$ mJy
- Wolf-Rayet stars, with similar fluxes (up to ≈ 380 mJy)
- hot stars with shells, a very heterogeneous class of objects with high millimeter fluxes, typically $\approx 100 - 500$ mJy (up to 1.6 Jy)

Table 1. Sample of millimeter continuum detections of stars

Star name	Stellar type	S_{1mm} (mJy)	Comments
P Cygni	LBV	146	Stellar wind source
η Carinae	LBV	16000	Wind + nebula; variable, extended
MWC 349	Bpe	1630	Bipolar outflow; extended
Cyg OB2-5	O	55	Stellar wind
WR 147	WR/O bin.	379	Somewhat peculiar binary system
WR 105	WR	48	Stellar wind
CRL 961	Massive YSO	465	Probably warm dust
MWC 957	Evolved	77	Flat spectrum; optically thin shell
VV Cep	M2Ia+B8V	45	Cool M-star wind ionized by B star
α Aur	G5III-G0III	23	Nearby binary; chromospheres?
α CMa	A1Vm	11	Nearby main-seq. A star; stellar disk
α CMi	F5IV	11	Nearby star; photosphere/chromosphere
Betelgeuse	M2I	351	Stellar disk
Mira	M7III	129	Warm dust in circumstellar shell
T Tauri	PMS	296	Dust in disk around low-mass PMS
HL Tau	PMS	961	Dust in disk around low-mass PMS
β Lyrae	B7Ve+?	56	Shell around binary system?
SS 433	XRB	112	Nonthermal synchrotron from jets?
Cyg X-3	XRB	20-260	Highly variable nonthermal source
AE Aqr	Mag. CV	24	Nonthermal; not well understood
UV Cet	dM5e	< 9	Flare star

- pre-main sequence (PMS) stars, including T-Tauri and post-T Tauri stars, FU Ori stars etc., with fluxes of $\approx 20 - 500$ mJy (up to 1.7 Jy).
- late-type giants and supergiants, including normal stellar photosheres as well as Miras and AGB stars with circumstellar envelopes (with typical fluxes of $\approx 10 - 100$ mJy, but up to 1.5 Jy in some cases).
- optically variable stars (another quite heterogeneous group of objects which includes flare stars, X-ray emitting accretion binaries, symbiotic stars, etc.) with fluxes in the range $\approx 20 - 300$ mJy.

Note that many of the 270 objects in this survey, from virtually all classes, were not detected at the sensitivity limit of $\approx 10 - 20$ mJy. In the following, we will discuss briefly these various types of objects, taking into account the Altenhoff et al. survey as well as the results of other millimeter observations obtained recently. Table 1 presents a sample list of 1 mm continuum detections of stars covering a wide range of stellar types.

3.1 Winds from Hot Stars

The radio emission from hot stars (including both O - B and Wolf-Rayet stars) is dominated by optically–thick free–free emission from their massive radiatively driven winds. Observations by Leitherer and Robert (1991) with the SEST 15m single-dish and by Altenhoff et al. (1994) with the IRAM 30m telescope, show that hot stars typically have millimeter radio spectra of the form $S_\nu \sim \nu^{0.67}$ expected for optically-thick thermal free-free emission from an isothermal spherically symmetric wind expanding at constant speed. For such a wind, the radio flux $S_\nu \propto \dot{M}^{4/3} \, {v_\infty}^{4/3} \, \nu^{2/3} \, d^{-2}$, where $\dot{M}$ is the mass loss rate, v_∞ is the wind terminal velocity, and d is the distance (e.g. Panagia and Felli 1975, Wright and Barlow 1975). The mass loss rates $\dot{M}$ derived at present from radio observations of hot stars are of the order of $\approx 10^{-5} M_\odot yr^{-1}$. However, since the mass loss rate scales as $\sim S_\nu^{3/4}$, the improved sensitivity of the LSA will extend the range of mass–loss rates amenable to study well below the current limit, which samples only the most extreme mass–loss rates in a given class of stars. Moreover, since the radial distance R_ν from which radiation of frequency ν originates scales as $\sim \nu^{-3/2}$, higher frequencies will sample regions closer to the stellar surface, allowing study of the region in which the wind is accelerated by optical/UV line emission.

The millimeter emission of Wolf-Rayet stars has properties similar to those of O - B stars, indicating that the emission mechanism is basically the same. However, deviations from the canonical $\sim \nu^{0.67}$ law are occasionally observed for Wolf-Rayet stars, implying that accurate determinations of the spectral slope from centimeter to millimeter wavelengths can provide important information on the structure of the wind and its ionization state.

Two stars in this class deserve specific mention: they are probably the brightest stellar millimeter radio continuum sources in the southern and northern skies, respectively. The massive southern "luminous blue variable" (LBV) η Carinae has a $\lambda = 1$ mm flux of up to 16 Jy (Cox et al. 1995), making it brighter than nearly all known calibrator sources. Further, the source is extended and the flux comes from a region of just a few arcseconds in extent, and is highly variable. The northern object MWC 349 is famous for its masing millimeter recombination lines (a property which it shares with η Car); at $\lambda = 3$ mm it has a flux of 1 Jy, and is also extended on a subarcsecond scale, showing a bipolar outflow and a circumstellar disk.

3.2 Be Stars and Other Hot Stars with Shells

Hot stars with shells (of which there is a variety of different types in the survey of Altenhoff et al.) are usually stronger at millimeter wavelengths than wind sources. The radio spectra show evidence for a turn-over around 5 -10 GHz from optically thick to optically thin emission. The spectrum at high frequencies is typically flat indicating optically thin shells. A contribution from warm dust may be present in some cases. An important class of hot stars with shells is represented by the Be stars for which millimeter observations have been obtained by Waters et al. (1989, 1991) at the JCMT in Hawaii. Observations of ψ Per and other Be stars show a steepening of the spectrum at 0.8 and 1.1mm with respect to IRAS data. This has important implications for the radial density distribution of the ionized gas in the circumstellar disk.

3.3 Stellar Photospheres

In stars without massive ionized outflows, the millimeter radiation may originate close to the stellar photosphere and (for a uniformly illuminated disk) the flux at 250 GHz is given by:

$$S_{250} = 1.4175 \times 10^{-4} \; T_{disk} \; r_{mas}^2 \tag{1}$$

where T_{disk} is the temperature of the emitting layer and r_{mas} is its radius in milliarcsec. For $T_{disk} \approx T_{eff}$ and $r_{mas} \approx R_*/d$, a sizeable number of nearby stars (mostly giants and supergiants) are predicted to be detectable at millimeter wavelengths even at the present sensitivity levels. About 50 were in fact detected in the survey of Altenhoff et al. at flux levels > 10 mJy at 250 GHz, and ≈ 600 were predicted to have fluxes > 1 mJy at 230 GHz by the MMA working group (Dulk et al. 1989). Since the number of detectable sources increases as $\sim S_{lim}^{-3/2}$ for a homogeneous spherically symmetric distribution, thousands of sources will be detectable at the very low flux limits (≈ 0.1 mJy) expected for the LSA, thus making the study of millimeter emission from normal stars a major field of investigation. The importance of millimeter observations in this field is that they are directly sensitive to the electron temperature in the atmosphere, and do not require assumptions such as LTE as does the analysis of optical and infrared spectra. For stars of known parallax and effective temperature, it will also be possible to measure stellar radii using (1) and the measured millimeter fluxes. Thus millimeter data can measure fundamental parameters a much larger range of stars than are presently known.

3.4 Other Late-type Giants and Supergiants

Millimeter emission was detected from the photospheres of many late-type giants and supergiants in the survey of Altenhoff et al., but not all of their detected cool giants and supergiants are "normal" giants. This group of stars also contains various classes of objects with ionized winds, such as VV Cep stars, and circumstellar envelopes in which dust may make a significant contribution to the radio emission (Miras, and AGB and post-AGB stars). All these are potentially interesting objects for high-sensitivity millimeter wavelength observations.

For example, symbiotic stars (studied at millimeter wavelengths by Seaquist and Taylor 1992 and by Ivison et al. 1992) are interacting binaries with mass transfer from a late-type giant to a compact object. Their spectra, obtained at JCMT, show, in combination with VLA and IRAS data, a variety of behaviours ranging from optically thick free-free emission all the way from centimeter to IR wavelegnths, to optically thick free-free emission plus a dust contribution at IR wavelengths, to a transition from optically-thick to optically thin emission plus a dust contribution at longer wavelengths. Millimeter observations are essential for studying these objects since they provide an important link between the centimeter data and the IR fluxes and allow the modelling of the ionized circumstellar enviroment. Similar considerations apply to VV Cep stars, which are main-sequence B stars orbiting a late-type supergiant. In this case, millimeter radiation originates from free-free emission in the massive wind of the cool supergiant which is ionized by UV from the B star.

Miras and Semi-Regular (SR) variables have been studied at millimeter wavelengths by Walmsley et al. (1992) using the IRAM 30m single dish at Pico Veleta. The observed millimeter radiation is mostly consistent with photospheric emission. Excess millimeter emission (at levels as high as $\approx 500 - 1500$ mJy) is observed in AGB and post-AGB stars (including proto-planetary nebulae): this arises from warm durst in the circumstellar envelopes of these stars.

3.5 Pre-Main Sequence Stars

Pre-main sequence stars (including classical and weak-lined T-Tauri stars, FU Ori stars and Herbig Ae/Be stars) constitute an important class of millimeter continuum sources (Beckwith et al. 1990; Weintraub et al. 1991, Henning et al. 1994, Osterloh and Beckwidth 1995; Dutrey et al. 1995). PMS stars have a high rate of detection in the Altenhoff et al. survey, with very high fluxes in some cases ($\approx 100{-}1000$ mJy). Their spectra have a spectral index $\alpha > 2$ from 5 to 250 GHz. All this is consistent with thermal radiation from cold dust in circumstellar disks, as first discussed by Beckwith et al. (1986). Millimeter continuum observations allow the determination of the mass of the disk, and more sensitive measurements should allow the determinations of the mass of thinner disks, which is important for weak-lined T-Tauri stars and post-T Tauri stars. A recent survey by Osterloh and Beckwidth (1995) has shown that the rate of detection of classical T-Tauri stars (CTT) is indeed higher than for the weak-lined T-Tauri stars (WTT), likely because the former have more massive circumstellar disks. Post-T Tauri stars (i.e. PMS stars that are older and more evolved than T-Tauri stars) are believed to lack dense circumstellar disks (Skinner et al. 1992, Gahm et al. 1994); yet a few of them (e.g. HD 560, Altenhoff et al. 1994) have been detected at millimeter wavelengths. This rises the question whether the observed emission is thermal radiation from very thin disks or rather non-thermal emission from flares in young stars characterized by strong magnetic activity. Dusty disks have also been observed around some main-sequence stars like Vega (Chini et al. 1990).

3.6 Optically Variable Stars

The class of optically variable stars in the survey of Altenhoff et al. is very heterogeneous and shows a low detection rate at the present sensitivity levels (only 15 of the 76 surveyed stars were detected, including 5 symbiotics). This class includes RS CVn binaries, flare stars, accretion-powered X-ray sources, β Lyrae binaries, and novae. In many cases, the emission mechanism is likely to be non-thermal. This is the case for instance of flares on RS CVn binaries and flare stars where one expects, by analogy with the Sun, that millimeter radiation originates from synchrotron emission of high energy electrons (> 1 MeV). The emission is expected to be highly variable, and so although $\lambda = 3$ mm fluxes in excess of 1 Jy may be expected at times of outburst, only a few RS CVn's have been detected so far (e.g. HR 1099, UX Ari, UV Psc) and no undisputed detection of flare stars has yet been reported (Lim and White 1995). The higher sensitivity of the LSA should contribute substantially to this area thus allowing the study in other stars of flares similar to, but much more energetic, than solar flares.

In accretion-powered X-ray sources (like SS433, Cyg X-1, Cyg X-3, etc), non thermal emission is expected to arise from the accreting flow, while in β Lyr variables it is unclear whether we are observing non-thermal emission or thermal emission from ionized shells. The magnetic cataclysmic variable AE Aqr has been detected at $\lambda = 3$ mm (Abada-Simon et al. 1993), and while the emission is clearly nonthermal there is no accepted model as yet. Finally, in novae (such as Nova Cyg 1992 studied by Ivison et al. 1993), the radio spectrum is consistent with thermal free-free emission from an expanding shell of ionized gas. Observations at different epochs after the explosion (including crucial millimeter observations) allow one to follow the evolution of the phenomenon and the transition from optically thick to optically thin emission in the expanding shell.

4 Conclusion

From the survey above, it is clear that a large variety of different stellar objects can emit millimeter continuum radiation. About one hundred stars have already been detected at millimeter wavelengths at flux limits $> 10 - 30$ mJy. The detected stars cover the entire HR diagram, but with present instruments only a handful of sources is available within each class. With the large sensitivity of the proposed LSA, it will be possible to detect several thousands of them and obtain statistically significant samples for each class. In some cases it should even be possible to resolve the sources, although the majority of stellar sources will remain unresolved if the spatial resolution is not significantly better than 0.1 arcsec. Continuum observations to be carried out with the LSA will have a strong impact on many stellar problems, such as:

- the winds of hot stars
- the circumstellar disks of PMS stars and Vega-type objects
- the upper photopheres and low chromospheres of giants and supergiants
- the non-thermal emission of RS CVn binaries, flare stars and accretion powered X-ray sources
- the winds of symbiotic stars and VV Cep stars
- the circumstellar shells of Be stars, AGB and post-AGB stars, planetary nebulae, and novae

To conclude, it can reasonably be expected that the proposed LSA will produce for radio stars a quantum jump as large as or larger than the one produced in the early eighties at centimeter wavelengths by the opening of the VLA.

References

Abada-Simon, M., Lechacheux, A., Bastian, T. S., Bookbinder, J., and Dulk, G. A. (1993) *Ap. J.* **406**, 692

Altenhoff, W.J., Thum, C., and Wendker, H.J. (1994) *A&A* **281**, 161

Bastian, T., Gagné, M., Gary, D., Gordon, M., Hjellming, R., Hogg, D., Lindsey, C., Kundu, M., Rabin, D., and White, S. (1995) *Report of the Working Group on "The Sun and Stars"*, Second MMA Science Workshop

Bechwith, S.V.W., Sargent, A.I., Scoville, N.Z., Masson, C.R., Zuckerman, B., and Phillips, T.G. (1986) *Ap. J.* **309**, 755

Beckwith, S.V.W., Sargent, A.I., Chini, R.S., and Güsten, R. (1990) *A.J.* **99**, 924

Chini, R., Krügel, E., and Kreysa, E. (1990) *A&A* **227**, L5

Cox, P., Mezger, P. G., Sievers, A., Najarro, F., Bronfman, L., Kreysa, E., and Haslam, G. (1995) *A&A* **297**, 168

Dulk, G.A. (1985) *Ann. Rev. Astron. Ap.* **23**, 169

Dulk, G.A., Gary, D.E., Hjellming, R.M., Kundu, M.R., and Bastian, T.S. (1989) *Report of the Working Group on "The Sun and Stars"*, First MMA Science Workshop

Gahm, G.F., Zinnecker, H., Pallavicini, R., Pasquini, L. (1994) *A&A* **282**, 123

Dutrey, A., Guilloteau, S., Duvert, G., Prato, L., Simon, M., Schuster, K., and Ménard, E. (1995) *A&A*, in press

Henning, Th., Launhardt, R., Steinacker, J., and Thamm, E. (1994), in *ASP Conference Series* **62**, 171

Ivison, R.J., Hughes, D.H., and Bode, M.F. (1992) *MNRAS* **257**, 47

Ivison, R.J., Hughes, D.H., Lloyd, H.M., Bang, M.K., and Bode, M.F. (1993) *MNRAS* **263**, L43

Kundu, M.R., White, S.M., Gopalswamy, N., and Lim, J. (1994) *Ap. J. Suppl.* **90**, 599

Leitherer, C., and Robert, C. (1991) *Ap. J.* **377**, 629

Lim, J., and White, S.M. (1996) *Ap. J. Letters*, submitted

Lim, J., White, S.M., Kundu, M.R., and Gary, D.E. (1992) *Solar Phys.* **140**, 343

Osterloh, M., and Beckwith, S.V.W. (1995) *Ap. J.* **439**, 288

Panagia, N., and Felli, M. (1975), *A&A* **39**, 1

Sargent, A.I., and Welch, W.J. (1993) *Ann. Rev. Astron. Ap.* **31**, 297

Seaquist, E.R., and Taylor, A.R. (1992) *Ap. J.* **387**, 624

Skinner, S.L., Brown, A., Walter, F.M. (1992) *A.J.* **102**, 1742

Walmsley, M., Chini, R., Kreysa, E., Steppe, H., Forveille, T., and Omont, A. (1991) *A&A* **248**, 555

Waters, L.B.F.M., Boland, W., Taylor, A.R., van de Stadt, H., and Lamers, H.J.G.L.M. (1989) *A&A* **213**, L19

Waters, L.B.F.M., van der Veen, W.E.C.J., Taylor, A.R., Marlborough, J.M., and Dougherty, S.M. (1991) *A&A* **244**, 120

Weintraub, D.A., Sandell, G., and Duncan, W.D. (1991) *Ap. J.* **382**, 270

White, S.M., and Kundu, M.R. (1992) *Solar Phys.* **141**, 347

Wright, A.E., and Barlow, M.J. (1975) *MNRAS* **170**, 41