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Potential Impact of the EVLA on Studies of Thermal Radio Emission from Cool Evolved K and M Star Winds

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Abstract. Cm-radio observations of evolved K and M stars made at the VLA and ATCA, and subsequent detailed atmospheric modeling, have revealed that the thermal emission originates from the wind acceleration region close to the star. The temperature and density gradients can only be coarsely described for the handful of stars with existing two or three wavelength detections. The EVLA will provide an order of magnitude increase in sensitivity over the VLA, coming mainly from the increase in available correlator band-width, and this will offer the opportunity to map the density and temperature structure of the stellar winds with unprecedented clarity.

We present new radio fluxes for cool evolved stars (α TrA K3 II, β Gru M5 III) and use these and existing data to examine the role that the EVLA will play in future wind studies.

1. Cool Star Winds

[*This is a reformatted and slightly expanded version of the Poster. Additional references to radio measurements and angular diameters are now given in a new Table 3 that could not be included on the original Poster.*]

Cool star winds are feeble thermal radio sources and the Very Large Array and the Australia Telescope Compact Array have only scratched the surface of the diagnostic potential of their cm-radio emission. One of the big surprises from ultraviolet studies with spectrographs on board the *Hubble Space Telescope* is that there is no detectable **wind emission** signature and therefore very little is known about wind temperatures. However, wind temperatures have proved to be an important constraint for theoretical models of mass loss and radio wind emission is currently the best thermal diagnostic of the acceleration region, i.e., within the first few stellar radii above the stellar surface.

Winds are continuum sources so that any increase in available bandwidth leads to an increase in sensitivity. Typical observations at the VLA have two 50 MHz bands for a total of 100 MHz bandwidth. The new *ultrasensitive* Expanded Very Large Array (EVLA) (also known as Phase I) will have GHz of bandwidth from 1-50 GHz. Here we investigate the impact that this new facility will have on cool star wind studies.

Figure 1 shows the predicted radio spectrum of the nearby galactic interloper Arcturus (K1.5 III) based on the chromosphere and wind scattering models of Drake (1985) which were based on an IUE spectrum on the Mg II k 2796Å. This figure shows the complementary nature of the EVLA and ALMA for cool

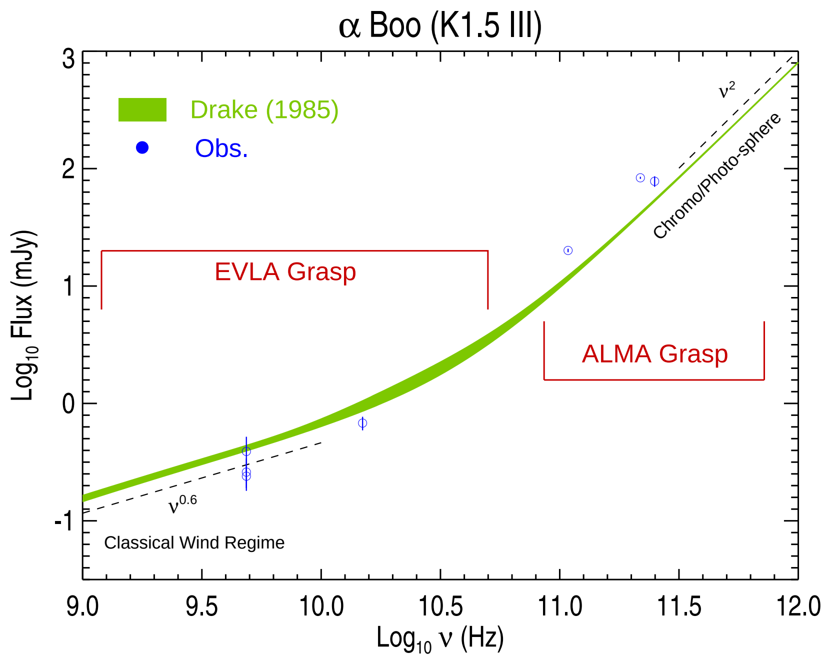

Figure 1. Predicted radio spectrum and observations of Arcturus. The observations shown in the EVLA grasp are from the VLA (Drake & Linsky 1986) and those in the ALMA grasp are from IRAM (Altenhoff et al. 1994) and BIMA (Cohen et al. 2005). The green shaded area is the envelope from Models A and B based on the IUE Mg II k profile (Drake 1985). At low frequencies the slope approaches the well known $\sim \nu^{0.6}$ limit when the wind has constant velocity, ionization and temperature, while at high frequencies the small density scale heights lead to a blackbody-like slope $\sim \nu^2$.

star atmosphere research. ALMA will sample the chromosphere and the base of the wind, while the EVLA will sample the wind acceleration region out into the asymptotic flow. The gently changing spectral slope shows that it is important to obtain high signal-to-noise ratio flux measurements at many frequencies to sample the changing temperature and density gradients.

2. Expanded Very Large Array

The large bandwidth of the EVLA is made possible by the use of a new signal processing *Wideband Interferometric Digital ARchitecture (WIDAR)*. The WIDAR correlator, described in Chapter 8 of the EVLA Project Book (Carlson et al. 2006), and build at the NRC-Dominion Radio Astrophysical Observatory, is capable of processing four pairs of oppositely polarized signals, each with up to 2.048 GHz bandwidth. However, the newly available frequencies also include radio frequency interference (RFI), especially at the longer wavelengths that sample the outer wind. Perley (2004) has outlined WIDAR suitable observing modes in the presence of RFI that (1) oversample the desired spectral resolution by a factor of two, and (2) use the 7-bit correlator mode. For wavelengths at C-band (6 cm) and longer this reduces the maximum bandwidth ($\Delta\nu$) available to 2 GHz. The predicted 1σ noise levels are given in Table 1.

Table 1. Adopted Sensitivity Parameters for EVLA. The 1σ noise level is computed using the high RFI observing mode (Perley 2004) with 27 antennae, system efficiency= 0.78, two recorded polarizations (RR and LL), and 4 hours on-source. Sensitivity parameters are from Napier (2004)

Band (cm)	Frequency (GHz)	Range (cm)	T_{sys} (K)	Antenna Efficiency	RFI Factor	$\Delta\nu$ (GHz)	1σ noise (μJy)
L	1-2	30-15	21	0.50	0.76	1	2.8
S	2-4	15-7.5	27	0.62	0.96	2	1.6
C	4-8	7.5-3.8	28	0.60	0.89	2	1.9
X	8-12	3.8-2.5	31	0.56	1.00	2	2.0
U	12-18	2.5-1.7	37	0.54	1.00	2	2.4
K	18-28	1.7-1.1	55	0.51	1.00	2	3.8
A	28-40	1.1-0.8	58	0.39	1.00	2	5.3
Q	40-50	0.8-0.6	78	0.34	1.00	2	8.1

To estimate the reduction in sensitivity resulting from RFI (the RFI Factor in Table 1) we find the fraction of channels (F_{clean}), whose spacing is determined by the 7-bit correlator mode, not affected by known RFI frequencies (Reynolds 2001; Mertely et al. 2003). The increase in the noise level is $\sim 1/\sqrt{F_{clean}}$.

3. Characteristic Wind Fluxes

Thermal radio emission comes from the Rayleigh-Jeans tail of the Planck function which is linear in temperature. The characteristic radio angular diameter is, therefore, the primary factor that determines the likelihood of detection. Here we use 3.54 cm fluxes as measures of wind emission as currently there is a sig-

Table 2. New Australia Telescope Compact Array Results.

	Flux (mJy) (1σ-error)	ν (MHz) central		Flux (mJy) (1σ-error)	ν (MHz) central
αTrA (K3 II)			βGru (M5 III)		
3 cm			3 cm		
1995 Apr 17	0.26 ± 0.05	8510	1997 Nov 17-18	0.80 ± 0.06	8636
1997 Nov 17-18	0.28 ± 0.08	8658			
6 cm			6 cm		
1997 Nov 17-18	0.22 ± 0.05	4796	1997 Nov 17-18	0.35 ± 0.06	4796

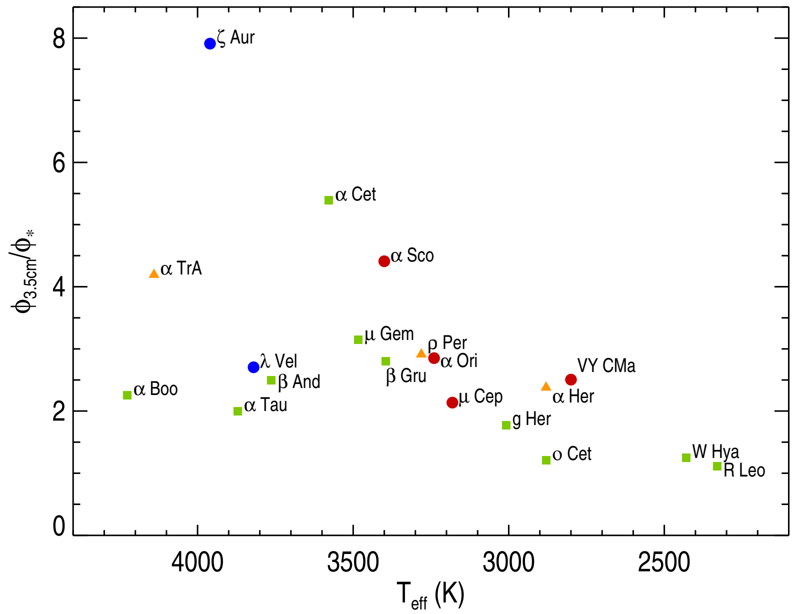

Figure 2. Characteristic wind-radio angular sizes. Luminosity class III giants (green squares) show a slow decline with decreasing T_{eff} that results from the balance between the increase in mass loss tempered by the winds being cooler and less ionized. Other symbols: orange triangles are luminosity class II bright giants, blue circles are luminosity class Ib supergiants, and red circles are luminosity class Ia & Iab supergiants. For a given mass loss rate the angular size increases if (1) the wind acceleration is slower, and (2) the wind is hotter and more ionized. The eclipsing binary ζ Aur (K4 Ib) has both (1) & (2).

nificant sample of detected sources in this band. To estimate the number of 5σ wind source detections possible with the EVLA at 3.5 cm (8.5 GHz) we have taken an inventory of VLA and ATCA $>3\sigma$ detections from the literature and the new detections shown in Table 2 and then estimated a character source size. For some stars that were detected at 2 cm and 6 cm we have interpolated to find a 3.5 cm flux. The references for the radio fluxes are given in Table 3.

Combining measured photospheric angular diameters ϕ_* (Mark III, NPOI, Masked Aperture) with inferred photospheric temperatures (T_{eff}), we derive the ratio of the radio to photospheric angular diameters, $\phi_{3.5cm}/\phi_*$, using the optically thick disk model, i.e.,

$$\frac{\phi_{3.5\text{cm}}}{\phi_*} = \frac{5\times10^3}{\phi_*(\text{mas})}\sqrt{\frac{F_{3.5\text{cm}}(\text{mJy})}{T_{\text{eff}}(\text{K})}}. \tag{1}$$

The derived values of $\phi_{3.5cm}/\phi_*$ are shown in Figure 2. The observed trends are then applied to stars in the *Hipparcos* (ESA 1997) and 2MASS (Cutri et al. 2003) catalogs using surface brightness relations to derive ϕ_* (Di Benedetto 1993) and T_{eff} from their spectral-types (Straižys 1992). [Note that here, for the purposes of estimating the number of stars that the EVLA will be able to detect, we have assumed that the 2MASS K magnitudes have the same surface

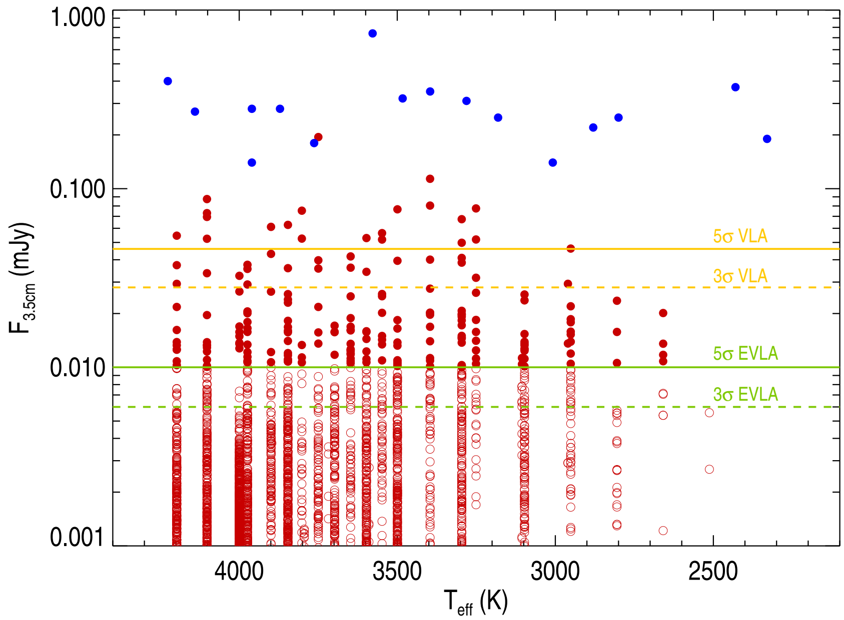

Figure 3. Predicted 3.54 cm fluxes for the *Hipparcos* Catalogue (ESA 1997) and 2 Micron All Sky Survey (Cutri et al. 2003) sample. 5σ (solid) and 3σ (dashed) detection thresholds are shown for the VLA and EVLA. The blue filled circles are VLA detections. We estimate that the EVLA could potentially detect 5 times the number of wind sources at 5σ than the VLA.

brightness relationships as Johnson K. Furthermore, some stars will have (partially) saturated 2MASS images and the K magnitudes will not be as accurate the main catalog.] The 3.54 cm radio fluxes from this large sample visible from New Mexico are then computed using Eq. (1) and are shown in red in Figure 3 along with previously detected stars shown in blue.

4. Conclusions

- The number of stars that can be studied at $\lambda < 3.5$ cm will increase by a factor of 5 compared to the VLA. This will allow the trends of wind velocity and temperature gradients to be studied as a function of spectral type which in turn will provide clues to the wind driving mechanisms.
- The projected EVLA 5σ detection limit is ~ 0.014 mJy at the longest wavelengths (20 cm) which means that stars with angular diameters $\geq 10 - 20$ mas, depending on wind temperature, can be studied in detail right across the 1-50 GHz radio spectrum for the first time.

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Table 3. References for 3.5 cm Radio Source Fluxes. The fluxes are either measured or interpolated and the spectral-types for the earlier spectral-types are mostly from Keenen & McNeil (1989). The sample of radio fluxes and stellar parameters is by no means homogeneous, e.g., some are mean values, the angular diameters are obtained at different wavelengths and have different limb darkening corrections applied (or not). Numerical values are references to radio measurements, and letters are references to angular diameters some of which also provide estimates for T_{eff}.

Star	Spectral Type	3.5 cm Flux (mJy)	Angular Diameter (mas)	T_{eff} (K)	References
α Boo	K1.5 III	0.40	21.4	4226	(01)(A)
α TrA	K2 II	0.27	9.6	4140	(02)(B)
ζ Aur	K4 Ib	0.28	5.3	3960	(03)(C)
λ Vel	K4.5 Ib	0.14	11.1	3820	(04)(D)
α Tau	K5 III	0.28	21.1	3871	(05,06)(A)
β And	M0 III	0.18	13.7	3763	(07)(A)
α Cet	M1.5 III	0.74	13.2	3578	(07)(A)
α Sco	M1.5 Iab-Ib	4.27	39.8	3400	(08)(A)
α Ori	M1-2 Ia-Iab	3.36	56.0	3240	(09)(E)
μ Cep	M2 Ia	0.25	20.6	3181	(07)(A)
μ Gem	M3 III	0.32	15.1	3483	(07)(A)
ρ Per	M4 II	0.31	16.6	3281	(01)(A)
β Gru	M4.5 III	0.79	27.0	3396	(02)(F)
α Her	M5 Ib-II	1.16	36.0	2880	(01)(A)
VY CMa	M5 Ia	0.25	18.7	2800	(10)(G)
g Her	M6 III	0.14	19.1	3008	(02)(A)
o Cet	M5-9 III	0.22	35.8	2880	(12)(H)
R Leo	M6-9 III	0.19	40.3	2330	(11)(H)
W Hya	M7-9 III	0.37	49.0	2430	(11)(H)

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(05) Wood et al. (2007)
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(09) From compilation in Harper et al. (2001)
(10) Lipscy et al. (2005)
(11) Reid & Menten (1997)
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(A) Mozurkewich et al. (2003)
(B) Cohen et al. (1996)
(C) Bennett et al. (1996)
(D) Blackwell & Shallis (1977)
(E) Bester et al. (1996)
(F) Bedding et al. (94)
(G) Monnier et al. (2004)
(H) Haniff et al. (1995)