A RADIO-CONTINUUM SURVEY OF THE COOLEST M AND C GIANTS

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Received 5 June 1987

ABSTRACT

We present the results of a sensitive VLA continuum survey of 22 cool M and C type giants and supergiants, including nine carbon stars, one S type star, and 12 M stars. The purpose of the survey was to probe the physical properties of the partially ionized, expanding chromospheres of the coolest luminous stars. Of the 22 stars observed at 6 cm, none were detected directly, although extended emission was detected near NML Cyg and OH 26.5 + 0.6, and a point source was detected near AFGL 865. Of the three stars observed at 2 cm, R Aql (M6.5e-9e) was detected as a 0.54 ± 0.17 mJy source, and a point source was detected 7" from R Cas (M6e-9e) and may be physically associated with the star. These data imply small upper limits for the ionized-mass-loss rates and 2-6 cm spectral indices that are significantly steeper than the 0.6 value predicted by the "standard" stellar-wind model. The typical fractional ionizations \( f_{\text{ion}} < 0.003 - 0.003 \) are considerably smaller than for the early M giants and supergiants, which indicates that hydrogen is predominately neutral and that carbon and other metals may not be completely once-ionized in many of the late M giants. For a number of the stars, the brightness-temperature upper limits imply that the winds and chromospheres are optically thin at 6 cm. This condition sets useful constraints on the chromospheric-emission measures for these stars. The nondetection of \( \sigma \) Ceti (Mira) at both 2 and 6 cm, despite a previous 6 cm detection, supports the idea that the radio-continuum emission of these stars may be variable, perhaps due either to flares or to the passage of pulsation-generated shock waves through their outer atmospheres.

I. INTRODUCTION

Extensive observations of the early M supergiant Betelgeuse = \( \alpha \) Ori (M2 Iab) have led to models for this star consisting of a partially ionized, extended, expanding chromosphere surrounded by an asymmetric, dusty circumstellar envelope. Properties of the chromosphere have been deduced from the infrared and microwave emission, with additional information from the ultraviolet emission lines (Linsky 1985) and Hα speckle images. From the 1.46-22.5 GHz continuum flux, Newell and Hjellming (1982) inferred that the chromosphere extends from about 1 to 4R, (stellar radii), that its temperature is roughly 7000-10 000 K, and that the electron density falls off with distance as \( n_e \sim (r/R)\sim^{3.59} \). Skinner and Whitmore (1987) are able to fit the observed infrared and radio emission by a model consisting of a 7000 K chromosphere out to 1.8 R, a partially ionized \( (n_e/n_H \approx 0.01) \) 8000 K wind extending out to 20R, and a circumstellar envelope with peak dust emission at 35R. Hartmann and Avrett (1984) have computed a detailed model for Betelgeuse consistent with the microwave spectrum in which the momentum and heating is provided by Alfvén waves. In their model the chromospheric temperatures lie above 5000 K between 1 and 9 R, the peak temperature of 8000 K occurs near 4R, and the fractional ionization \( (n_e/n_H) \) varies with height but lies in the range 0.001-0.06. Images of Betelgeuse in the Hα line using the differential speckle-interferometry technique provide direct evidence that the chromosphere extends out to at least 3R, (Beckers 1985). Beyond the chromosphere lies a circumstellar envelope with temperatures decreasing from 1200 K at the inner dust-shell boundary, and with a fractional ionization \( \sim 10^{-4} \) determined by the interstellar and chromospheric ultraviolet radiation fields (Glassgold and Huggins 1986). The inner boundary of the circumstellar envelope indicated by the onset of infrared dust emission occurs at about 10R, (Sutton et al. 1977; Low 1979; Bloemhof, Townes, and Vanderwyck 1984), although Roddier, Roddier, and Karovska (1985) provide visual images that indicate that dust scatters starlight as close in as 2.5R.

Betelgeuse is the most readily studied M supergiant because of its large angular diameter and brightness. It is important to determine, however, whether the previously described model for this star is a useful prototype for all cool giants and supergiants, or whether it is appropriate only for the early M supergiants. In particular, we would like to know whether chromospheres also exist in the later M and C giants and supergiants, including the Mira variables and the SiO maser stars.

Jennings and Dyck (1972) noted that Ca II H and K emission is inversely correlated with 10 \( \mu \)m dust emission, and proposed that dust formation in the later M supergiants "quenches" chromospheres by radiating away the energy that would otherwise heat the gas to chromospheric temperatures. To test this scenario, Stencel, Carpenter, and Hagen (1986) used IUE to observe the ultraviolet spectra of 14 M giants and supergiants known to show 10 \( \mu \)m dust emission. All of their stars (with spectral types as late as M5 III) exhibit emission features of Mg II, Fe II, Al II, and C II, indicative of plasma at chromospheric temperatures, but...
with radiative-loss rates a factor of 10 smaller than similar stars with little dust. High-resolution IUE spectra of such M giants as γ Cru (M3 III) (Wing, Carpenter, and Wahlgren 1983), β Gru (M5 III) (Judge 1986a), ρ Per (M4 II–III), 2 Cen (M5 III), and g Her (M6 III) (Eaton and Johnson 1987) also confirm the presence of numerous chromospheric ions in the spectra of these early and mid M giants. Finally, these chromospheric ions are also present in the low-resolution spectra of N type carbon stars (Johnson and O'Brien 1983; Johnson, Ake, and Eaton 1985), the S star γ Cyg (Cassatella et al. 1980a), and the oxygen-rich stars R Leo (M7e–9e III), R Dor (M6 III), and R Aql (M6.5e–9e III) observed by Wing and Carney (1978) and Kafatos, Michalitsianos, and Hobbs (1980).

In a comparative study of α Boo (K2 III), α Tau (K5 III), and β Gru (M5 III) based on high-resolution IUE spectra, Judge (1986a, b) concludes that the chromospheres of mid M giants are qualitatively similar to the warmer K giants. In particular, (1) the ionization equilibria of the metals are controlled by radiative processes, with photoinionization mainly by Lyα, and the first ions are generally the dominant stage of ionization except for oxygen (cf. Eaton and Johnson 1986); (2) ultraviolet emission lines of the once-ionized metals are likely formed at temperatures of 5000–9000 K, where hydrogen is predominately neutral; (3) the chromospheres are turbulent and perhaps inhomogeneous; (4) fluorescent processes often control the excitation of emission lines; and (5) ratios of C II intersystem lines imply electron densities of \( 3 \times 10^5 \) to \( 10^6 \) cm\(^{-3} \) and collisional excitation of these lines in a region of thickness \( \lesssim 0.2 \alpha_R \), although the region where resonance line photons (e.g., Mg ii h and k) are scattered is likely to be much more extended (see, for example, Drake and Linsky 1983a; Drake 1985). Judge (1986a) also notes trends of decreasing chromospheric electron density and the emission-line surface fluxes (and thus local heating rates), consistent with the conclusions of Stencel et al. (1986).

Outer atmospheric models derived from ultraviolet spectroscopic data are significantly different from the models derived from observations of 43 and 86 GHz SiO maser emission, which has been detected from \( \sim 100 \) oxygen-rich (and a few S type) red giants and supergiants (cf. Engels 1979; Jewell et al. 1985) with spectral types M4 and later. VLBI observations of such masers (Moran et al. 1979; Lane 1982) have shown that the maser emission originates from within a few stellar radii of the photosphere. Detailed modeling of the SiO maser mechanism (e.g., Elitzur 1980; Langer and Johnson 1982; Alcock and Ross 1986) appears to rule out its formation in a spherically symmetrical wind region. The cool regions (\( T_e \gtrsim 2500 \text{ K} \)) where the individual maser components are located may be in either giant convective cells in the photosphere (Elitzur 1980) or in dense clumps of gas in the inner wind region (e.g., Lane 1982; Alcock and Ross 1986). Some of the same late M stars that have the ultraviolet emission lines indicative of the existence of chromospheres (e.g., γ Cyg, R Aql, R Dor, and R Leo) are also confirmed SiO maser sources, implying that plasma of very different temperatures (\( T_e \gtrsim \) 8000 K and \( T_e \approx 2000 \text{ K} \)) coexists in the immediate vicinity (\( R \lesssim 2R_\odot \)) of the photospheres of these stars. Muchmore, Nuth and Stencel (1987) have proposed that this is due to a radiative-cooling instability.

We conclude that plasma at chromospheric temperatures exists even on the very coolest giants, but more studies are required to determine the amount of ionized plasma, its geometrical extent, and its fractional ionization, whether the chromosphere is permanent or just a temporary phenomenon that occurs only at certain pulsational phases, and whether the Betelgeuse model is a useful prototype for these stars. We also wish to learn whether there are any differences in the answers to the above questions between the early to mid M giants on the one hand, and the late M giants (which are often SiO maser sources) on the other. Since a partially ionized chromosphere emits free-free microwave radiation, which can be used to infer answers to all of these important questions, we proposed a sensitive 6 cm survey of a sample of these stars with the VLA.

Previous searches for radio-continuum emission in late M and C giants and supergiants have mostly yielded negative results, or (in the case of some single-dish telescope observations) uncertain transient emission. For example, Wilson (1971) "tentatively" detected at 0.35 cm the stars VY CMa (M5 Ia) and IRC +10216 (C9.5) at levels of 200 mJy (3σ) and 400 mJy (2σ), respectively, out of 12 infrared-strong stars observed. Schwartz and Spencer (1977) confirmed the radio emission of IRC +10216 with a detection of 145 ± 39 mJy at 0.33 cm but not that of VY CMa (70 ± 70 mJy) at this wavelength. Woodsworth and Hughes (1973) reported observing a 240 mJy flare at 2.8 cm from R Aql (M6.5e), with a post-flare level of 50 mJy. Fix and Spangler (1976) monitored nine M giants (including R Aql) at 70 cm for a period of 21 days, but they found no evidence for variability above their 10 mJy noise level. Bowers and Kundu (1979, 1981) reported detecting R Aql at 2 cm at a level of 5.3 ± 2.0 mJy, much weaker than the previous "flare" detection level of Woodsworth and Hughes (1973), but they did not detect this star at 6 cm above a detection limit of 2 mJy. Spergel, Giuliani, and Knap (1983) detected only two of 30 late M and C giants surveyed at 6 cm with the VLA: α Ceti (M5e–9e + wd?) at 0.74 ± 0.25 mJy and IRC +10216 at 0.42 ± 0.10 mJy. Herman, Baud, and Habies (1985) did not detect any of the 12 OH/IR stars they observed at 6 cm above a detection threshold of 0.1 mJy.

Drake and Linsky (1983b) detected 6 cm emission from α1 Her (M5 II) and inferred a fractional ionization of 0.002–0.02 in its expanding chromosphere. In their subsequent 6 cm survey, Drake and Linsky (1986, hereafter referred to as DL) detected three K and M giants (α Boo (K2 III), ρ Per (M4 II) and μ Gem (M3 III)) and possibly detected β UMi (K4 III). In Table 1, we collect all the published radio-continuum data on M and C giants and supergiants later than spectral type M4 (if oxygen rich) for which there is at least one claimed radio detection. Of these seven detected stars, only two, IRC +10216 and α1 Her, could be regarded as certain radio sources.

We present here the results of a sensitive 6 cm VLA survey of a sample of the brighter (and hence presumably closer) evolved stars consisting of nine carbon stars, one S type star, and 12 M giants and supergiants, including three of the five "possible" radio sources listed in Table I (V Cyg, α Ceti, and R Aql). Except for α Ceti, these are single stars and thus do not have hot secondary companions to provide additional ionization to the wind. All of the oxygen-rich stars in the present survey, and the S star γ Cyg, are known to be SiO masers (Engels 1979; Spencer et al. 1981). These stars, both oxygen rich and carbon rich, have effective temperatures in the general range 2000–3500 K. The rms noise levels of the maps constructed from our 6 cm radio observations lie in the range 0.03–0.07 mJy. For several of the stars, we made addi-
<table>
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<tr>
<th>Star</th>
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<th>Wavelength (cm)</th>
<th>Flux density (mJy)</th>
<th>Radio telescope</th>
<th>Reference</th>
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<td>MPIR 100m</td>
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<td>ζ² RZ Ari</td>
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II. RADIO-EMISSION MECHANISMS IN LATE M GIANTS

Drake and Linsky (1986) discussed various plausible radio-emission mechanisms for G to mid M giants. We restrict ourselves here to a brief summary of stellar-wind type models and other possible sources of radio-continuum emission that must contribute at some level.

a) Free-Free Emission from Partially Ionized Stellar Winds

The standard Wright and Barlow (1975) and Panagia and Felli (1975) models, which predict the observed radio flux $S_v$ from the completely ionized, optically thick stellar winds of hot stars, can be applied to cool stars by replacing the total mass-loss rate $M_{ion}$ by the mass-loss rate for the ionized material $M_{ion}$ where, in general, the ionization fraction $f_{ion}$ is in yr$^{-1}$, $v_w$ is the wind velocity in km s$^{-1}$, $D$ is the distance in kpc, $v_0$ is the frequency in units of GHz, and $T_4$ is the wind temperature in units of 10$^4$ K. The effective angular diameter (in milliarcseconds) of the radio-emission region is

$$\phi_e = 73.9 \frac{D}{v_0^2} T_4^{-0.5}.$$  

(2)

If this calculated value of $\phi_e$ is less than the stellar photospheric angular diameter $\phi_p$, then the wind cannot be optically thick. Assuming optically thin radio emission, the expected flux density in milliJanskys can be shown to be (cf. DL Eq. 3)

$$S_v = 1.6 \times 10^{11} \frac{M_{ion}}{v_w} D^{-2} v_0^2 T_4^{0.1},$$  

(1)

where $S_v$ is in mJy, $M_{ion}$ is in $M_\odot$ yr$^{-1}$, $v_w$ is the wind velocity in km s$^{-1}$, $D$ is the distance in kpc, $v_0$ is the frequency in units of 5 GHz, and $T_4$ is the wind temperature in units of 10$^4$ K. The effective angular diameter (in milliarcseconds) of the radio-emission region is

$$\phi_e = 4.4 \times 10^9 \frac{M_{ion}}{v_w} D^{-2} v_0^{-1} T_4^{0.35} R_4^{-1},$$  

(3)

where the photospheric radius in solar radii now explicitly enters. The above equations implicitly assume that $v_w, T_4, M_{ion}$, and $f_{ion}$ are constant throughout the radio-emission region. Such assumptions are unlikely to be accurate; however, given the relatively small spatial scale of the chromospheres of these stars, these assumptions should not result in large errors in the derived parameters. In any case, there are few, if any, models available that could be used to make more realistic assumptions.

When there is an outer cutoff radius $r_o$ (with an equivalent angular diameter $\phi_o$) to the radio-emission region (caused, for example, by an abrupt decline in the ionization fraction), Moran (1983) showed that there will be a critical frequency $\nu_c$ such that, for $\nu_c < \nu_0, \phi_o = \phi_0$ and $S_v \propto \nu_0^{-1}$. It is plausible to identify the inner edge of the dusty, molecular-shell region in the winds of late M giants with this cutoff radius. Detailed models of the circumstellar envelope of the M supergiant $\alpha$ Ori (Glassgold and Huggins 1986) show a rapid decline in $f_{ion}$ of between a factor of 10 and 100 in this "chromosphere/dust-zone transition region," providing some support to the concept of a sharp cutoff radius for free-free emission. Rowan-Robinson and Harris (1982, 1983a,b) have modeled the infrared emission from many late-type evolved stars, including all the stars in the present sample, using as one of their model parameters $r_o$, the inner edge of the dust shell. The angular diameter $\phi_o$ corresponding to $r_o$ for the stars in the present sample (see Table II) ranges from about 10 mas for AGFL 482 to about 1" for $\sigma$ Ceti. Assuming $\phi_o = \phi_0$ and $S_o = 1$ mJy, the predicted critical frequencies lie in the range from 37 GHz to 370 MHz for the above range of values of $\phi_0$.

b) Stellar Disk Emission

All stars are thermal continuum sources due to their temperature and finite solid angle. If stars were perfect blackbodies with brightness temperature $T_{bol} (= T_{eff})$ and $\phi = \phi_0$, then the observed flux density would be

$$S_v (\text{mJy}) = 1.42 \times 10^{-4} \left(\frac{T_{bol}}{10^4 \text{ K}}\right)^{0.1} \phi_0 v_0^2.$$  

(4)

In fact, the brightness temperature of a star at radio frequencies is a function of the electron temperature in the region where $\nu = \nu_c$ is reached. For the quiet Sun radio emission, $T_4$ (2 cm) $= 1.2 \times 10^4$ K and $T_4$ (6 cm) $= 2.4 \times 10^4$ K (Fürst 1980). For M giants with no plasma above their photospheres hotter than about $1.5 \times 10^4$ K, $T_4$ must presumably lie between $\sim 2 \times 10^4$ K and $1.5 \times 10^4$ K. The stars in the present survey have values of $\phi_0$ (inferred and/or directly measured) between 2 and 53 mas, and assuming $T_4 \approx 1$, the expected flux densities range from 0.5 mJy to 0.4 mJy at 6 cm and from 5 mJy to 3.6 mJy at 2 cm. The stars in our sample for which the stellar disk emission should be detectable above 0.1 mJy at 6 cm are $\gamma$ Cyg ($\phi_0 \approx 35$ mas), R Cas ($\phi_0 \approx 27$ mas), $\sigma$ Cet ($\phi_0 \approx 32$–52 mas), R Leo ($\phi_0 \approx 40$–76 mas), W Hya ($\phi_0 \approx 53$ mas), and R Hya ($\phi_0 \approx 37$ mas).

c) Variable Emission from Shock Waves or Flares

In addition to quiescent or slowly varying (timescales of years) radio emission, there may also be transient emission mechanisms. At least half the stars in the present sample are pulsating Mira variables. These pulsations produce shock waves that propagate through the extended circumstellar envelopes, with resultant postshock regions that have temperatures sufficient for hydrogen Balmer-line emission ($T_4 > 8 \times 10^3$ K). Recent models of this phenomenon include those of Fox and Wood (1985) and Bertschinger and Chevalier (1985). The inferred shock-propagation speeds of $\sim 25$ km s$^{-1}$ should lead to characteristic timescales of months to years for (thermal) radio emission produced by these partially ionized postshock regions. Shocks may also be sources of synchrotron emission: White (1985) has modeled the observed, highly variable radio emission from luminous hot stars with strong stellar winds, by assuming that shock waves propagating through the winds can accelerate electrons to relativistic energies. No detailed models yet exist for nonthermal radio emission produced in an analogous way by shocks in Mira winds, but the much smaller emission measure of ionized material in the Mira winds suggests that any possible nonthermal radio emission would be much weaker than for the OB supergiants.
Flares may be another source of variable radio emission from late-type stars. There is a wide range of timescales associated with radio emission from the active Sun, ranging from milliseconds ("spikes") to weeks (the slowly varying or "S" component). How such phenomena should be scaled in either energy or duration to M giants that lack coronae is highly speculative. Radio flares of M giants and supergiants occur fairly frequently. There are only a few reports in the literature of such events: the 240 mJy flare reported by Woodworth and Hughes (1973) from R Aql at 2.8 cm had a rise time of < 25 min and a decay time of hours. Despite considerable monitoring, no radio emission of this magnitude has been seen subsequently from this star. Kellerman and Pauliny-Toth (1966) reported a 110 mJy flare at 1.9 cm from α Ori (M2 Iab), although their time resolution was low (~ 1 day). This star has been observed frequently for the last ten years (e.g., Newell and Hjellming 1982): its typical "quiescent" emission levels range from 15 mJy at 1.3 cm to 0.4 mJy at 20 cm, but it has never been observed subsequently above 25 mJy at centimeter wavelengths. Boice et al. (1981) reported a 1 Jy radio flare at 70 cm from the M2 III star α Cer lasting 30 s, the only such event seen in about 50 hr of interference-free monitoring. All these reported flares from M giants were observed with single-dish radio telescopes and hence are subject to interference and/or confusion. Even if these flares were stellar, they appear to occur infrequently enough that the probability of observing any of the stars flare in our present survey is very small.

III. RESULTS

The survey was carried out from March 1984 to September 1985 on four different dates and in either B/C hybrid or C configurations of the NRAO Very Large Array.* All 22

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*The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract with the National Science Foundation.
stars were observed at 6 cm: o Cet, R Aql, and R Cas were also observed at 2 cm. The data were calibrated using the standard NRAO software. The 256×256 pixel maps were made from the u-v database using the AIPS system, and cleaned, when necessary, to remove sidelobes of strong extragalactic sources in the field. We list in Table II the adopted stellar positions and quality flags (A, B, or C) describing the estimated approximate accuracy to which the positions are known, which range from |Δα| < 1° (A), ~2°-7° (B), to ~15°-30° (C). The highest-quality positions come mostly from the SAO Catalog (including proper motion to the epoch of observation), with the following exceptions: the position for R Cas is an optical astrometric position taken from Soulié and Baudry (1983), and those for OH 26.5 + 0.6, IRC + 10011, and NML Cyg are from Bowers, Johnston, and Spencer (1983) and are based on OH maser observations at 1612 MHz. The B quality positions are from the IRAS Point Source Catalog (Beichman et al. 1985) and the estimated accuracy is taken from Hackings et al. (1985). The position for IRC — 10236 is that given in the IRC Catalog (Neugebauer and Leighton 1969) and is uncertain to ±15°-30° in right ascension (C quality).

Radio maps were constructed and examined for point sources near the nominal optical/infrared positions. The radio-reference-frame positions should be accurate to ~0.2°. The fundamental results of our survey as listed in Table III include the measured flux densities S at the nominal source positions (or 3σ upper limits in the absence of a source), and the inferred brightness temperatures T_b (Eq. (4)), radio angular diameters θ_rad (Eq. (2)) (both in milliarcseconds and in multiples of φ), ionized mass-loss rates η ion from Eq. (1), and from Eq. (3) when θ_rad < 1.1φ, and ionization fractions f ion. Radio sources were found within the error boxes surrounding the optical/IR positions only in the following cases.

a) R Aql at 2 cm

A point source of 0.54 ± 0.17 mJy (3.2σ) is present in our 2 cm map within 0.15 of the optical position, but no corresponding source is in our 2 cm field ( < 0.19 mJy (3σ)). We consider this detection probable because: (i) there is excellent positional agreement, (ii) the source has a thermal spectrum unlike most extragalactic sources, and (iii) there have been previous reported radio detections, albeit at higher levels.

The 2 cm flux of R Aql reported here is 100–500 times smaller than the flare values of 50–240 mJy reported by Woodsworth and Hughes (1973), and ten times smaller than reported by Bowers and Kundu (1979), suggesting that even the latter value represented a small flare event or was spurious. Assuming that our flux density is typical of R Aql when quiescent, it could be explained either by a stellar wind or a stellar disk type mechanism. Assuming the latter, then the radio brightness temperature is ridiculously high (T_b ~ 2 × 10^4 K). The only remaining possibility is that the star was flaring with an inferred 6 cm radio luminosities of 10^33 erg s^{-1} Hz^{-1}; this is somewhat less energetic than the previously reported radio flares of R Aql (10^{34} erg s^{-1} Hz^{-1} at 2.8 cm) and a Ori (10^{35} erg s^{-1} Hz^{-1} at 2 cm), and so cannot be ruled out. If the flare interpretation is correct, then the radio source will be undetectable when this field is reobserved, since the probability of catching another radio outburst should presumably be very small. If, on reobservation, the 6 cm radio source were still present at the 1 mJy level with a nonthermal spectrum, then it must be a background extragalactic source unrelated to AFGL 865.

d) NML Cyg and OH 26.5 + 0.6 at 6 cm

There is extended emission present in the VLA maps of both targets. In Fig. 1 we show our cleaned map of the region.
Table III. Radio data for survey stars.

<table>
<thead>
<tr>
<th>Star</th>
<th>Observing run</th>
<th>$S_\nu$ (mJy)</th>
<th>$T'_\nu$ (10^8 K)</th>
<th>$\phi_{\text{int}}$ (mas)</th>
<th>$\phi_{\text{int}}/\phi_r$</th>
<th>$v_\nu$ (km s$^{-1}$)</th>
<th>$x_{\text{int}}^b$ (yr$^{-1}$)</th>
<th>$f_{\text{int}}^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>IRC - 10236</td>
<td>III</td>
<td>&lt;0.15</td>
<td>&lt;24</td>
<td>&lt;29</td>
<td>&lt;4.3</td>
<td>11</td>
<td>&lt;4.3 x 10^-9</td>
<td>&lt;2.0 x 10^-3</td>
</tr>
<tr>
<td>CIT 6</td>
<td>III</td>
<td>&lt;0.17</td>
<td>&lt;5.0</td>
<td>&lt;31</td>
<td>&lt;2.0</td>
<td>17</td>
<td>&lt;4.6 x 10^-9</td>
<td>&lt;5.4 x 10^-4</td>
</tr>
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<td>IRC + 40540</td>
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<td>&lt;0.15</td>
<td>&lt;9.1</td>
<td>&lt;29</td>
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<td>15</td>
<td>&lt;1.3 x 10^-8</td>
<td>&lt;5.6 x 10^-4</td>
</tr>
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<td>IRC + 20370</td>
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<td>&lt;0.15</td>
<td>&lt;11</td>
<td>&lt;29</td>
<td>&lt;2.9</td>
<td>16</td>
<td>&lt;1.1 x 10^-8</td>
<td>&lt;1.0 x 10^-3</td>
</tr>
<tr>
<td>R Scl</td>
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<td>&lt;0.15</td>
<td>&lt;7.0</td>
<td>&lt;29</td>
<td>&lt;2.3</td>
<td>25</td>
<td>&lt;6.1 x 10^-9</td>
<td>&lt;6.9 x 10^-4</td>
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<td>16</td>
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</tr>
<tr>
<td>AFGL 865</td>
<td>III</td>
<td>&lt;0.18</td>
<td>&lt;41</td>
<td>&lt;31</td>
<td>&lt;5.7</td>
<td>15</td>
<td>&lt;2.5 x 10^-8</td>
<td>&lt;1.6 x 10^-3</td>
</tr>
<tr>
<td>V Cyg</td>
<td>IV</td>
<td>&lt;0.15</td>
<td>&lt;5.1</td>
<td>&lt;29</td>
<td>&lt;2.0</td>
<td>13</td>
<td>&lt;5.6 x 10^-9</td>
<td>&lt;1.2 x 10^-3</td>
</tr>
<tr>
<td>AFGL 3068</td>
<td>IV</td>
<td>&lt;0.15</td>
<td>&lt;264</td>
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<td>&lt;14.3</td>
<td>14</td>
<td>&lt;1.8 x 10^-4</td>
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<tr>
<td>η Cyg</td>
<td>I</td>
<td>&lt;0.09</td>
<td>&lt;0.52</td>
<td>&lt;22</td>
<td>&lt;0.63</td>
<td>10</td>
<td>&lt;1.0 x 10^-10</td>
<td>&lt;8.5 x 10^-4</td>
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<tr>
<td>OH 26.5 + 0.6</td>
<td>III</td>
<td>&lt;0.32</td>
<td>&lt;37</td>
<td>&lt;42</td>
<td>&lt;5.4</td>
<td>15</td>
<td>&lt;8.0 x 10^-8</td>
<td>&lt;3.8 x 10^-4</td>
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<tr>
<td>R Aql</td>
<td>III</td>
<td>&lt;0.19</td>
<td>&lt;5.7</td>
<td>&lt;32</td>
<td>&lt;2.1</td>
<td>8</td>
<td>&lt;1.3 x 10^-9</td>
<td>&lt;4.5 x 10^-4</td>
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<tr>
<td>NML Cyg</td>
<td>III</td>
<td>&lt;0.24</td>
<td>&lt;6.2</td>
<td>&lt;36</td>
<td>&lt;2.2</td>
<td>28</td>
<td>&lt;2.4 x 10^-7</td>
<td>&lt;5.3 x 10^-4</td>
</tr>
<tr>
<td>R Cas</td>
<td>III</td>
<td>&lt;0.16</td>
<td>&lt;1.6</td>
<td>&lt;30</td>
<td>&lt;1.1</td>
<td>12</td>
<td>&lt;5.3 x 10^-10</td>
<td>&lt;1.9 x 10^-3</td>
</tr>
<tr>
<td>IRC + 10011</td>
<td>III</td>
<td>&lt;0.18</td>
<td>&lt;9.0</td>
<td>&lt;31</td>
<td>&lt;2.7</td>
<td>23</td>
<td>&lt;3.4 x 10^-8</td>
<td>&lt;6.9 x 10^-4</td>
</tr>
<tr>
<td>α Cet</td>
<td>III</td>
<td>&lt;0.23</td>
<td>&lt;1.4</td>
<td>&lt;35</td>
<td>&lt;1.05</td>
<td>4</td>
<td>&lt;6.0 x 10^-11</td>
<td>&lt;1.7 x 10^-3</td>
</tr>
<tr>
<td>IRC - 10529</td>
<td>IV</td>
<td>&lt;0.15</td>
<td>&lt;21</td>
<td>&lt;29</td>
<td>&lt;4.0</td>
<td>16</td>
<td>&lt;4.0 x 10^-9</td>
<td>&lt;4.9 x 10^-4</td>
</tr>
<tr>
<td>U Ori</td>
<td>I</td>
<td>&lt;0.13</td>
<td>&lt;4.1</td>
<td>&lt;27</td>
<td>&lt;1.8</td>
<td>3.5</td>
<td>&lt;3.2 x 10^-10</td>
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</tr>
<tr>
<td>R Leo</td>
<td>I</td>
<td>&lt;0.10</td>
<td>&lt;0.43</td>
<td>&lt;0.58</td>
<td>4</td>
<td>9</td>
<td>&lt;9.3 x 10^-11</td>
<td>&lt;4.7 x 10^-3</td>
</tr>
<tr>
<td>RX Boo</td>
<td>II</td>
<td>&lt;0.15</td>
<td>&lt;1.7</td>
<td>&lt;29</td>
<td>&lt;1.1</td>
<td>11</td>
<td>&lt;9.9 x 10^-10</td>
<td>&lt;6.5 x 10^-3</td>
</tr>
<tr>
<td>W Hya</td>
<td>II</td>
<td>&lt;0.10</td>
<td>&lt;0.25</td>
<td>&lt;23</td>
<td>&lt;0.44</td>
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<td>&lt;1.0 x 10^-10</td>
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<tr>
<td>R Hya</td>
<td>I</td>
<td>&lt;0.10</td>
<td>&lt;0.51</td>
<td>&lt;23</td>
<td>&lt;0.63</td>
<td>3.5</td>
<td>&lt;7.4 x 10^-11</td>
<td>&lt;1.0 x 10^-4</td>
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</tbody>
</table>

(a) 6 cm Radio observations

<table>
<thead>
<tr>
<th>Star</th>
<th>Observing run</th>
<th>$S_\nu$ (mJy)</th>
<th>$T'_\nu$ (10^8 K)</th>
<th>$\phi_{\text{int}}$ (mas)</th>
<th>$\phi_{\text{int}}/\phi_r$</th>
<th>$v_\nu$ (km s$^{-1}$)</th>
<th>$x_{\text{int}}^b$ (yr$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R Aql</td>
<td>III</td>
<td>0.54 ± 0.17</td>
<td>1.80</td>
<td>18</td>
<td>1.2</td>
<td>8</td>
<td>α_{21 cm} &gt; 0.91</td>
</tr>
<tr>
<td>R Cas</td>
<td>III</td>
<td>&lt;0.51</td>
<td>&lt;0.55</td>
<td>&lt;18</td>
<td>&lt;0.65</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>α Cet</td>
<td>III</td>
<td>&lt;0.47</td>
<td>&lt;0.33</td>
<td>&lt;17</td>
<td>&lt;0.50</td>
<td>4</td>
<td></td>
</tr>
</tbody>
</table>

(b) 2 cm Radio observations

This picture can be compared with Fig. 1 of Habing, Goss, and Winnberg (1982), who observed this same region at 21 cm with the Westerbork Synthesis Radio Telescope at five times lower angular resolution (beam area = 766 arcsec$^2$). Their data clearly show the long north–south arc A of radio emission, but they could not resolve the shorter arc B. They

around NML Cyg. A long north–south arc of 6 cm emission (labeled A) lies to the west of the position of NML Cyg, with the peak flux of ~0.3 mJy beam, where the beam area is 29 arcsec$^2$, about 45° southwest of the star. A second arm of emission extends from the peak flux position almost directly towards the stellar location, terminating about 5° short of it.

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identify A with a faint H II region visible on the Palomar Sky Survey and give several arguments for its being associated with NML Cyg. The case for association is strengthened by the discovery of the second radio arc B. We also have detected the source 33W 15 mentioned by Habing et al. (1982); it is unresolved and has a flux density of $4.0 \pm 0.1 \text{ mJy}$ and lies at $(\alpha = 20^h 44' 27'17, \delta = 39^\circ 55' 21'0)$. Since its flux at 21 cm is 10.5 mJy, and its spectral index is nonthermal, it is probably an extragalactic source.

IV. DISCUSSION

No 6 cm radio source has been identified with a target star out of 22 observed, and one 2 cm radio source has a stellar counterpart (R Aql) out of only three stars observed at this wavelength. In addition, extended emission was detected near NML Cyg and OH 26.5 + 0.6 at 6 cm, and a point source at 2 cm was detected near R Cas. This contrast in success ratio between 6 and 2 cm is consistent with the spectral indices $\alpha_{2-6}$ of late M stars being very steep. The inferred value of $\alpha_{2-6}$ for R Aql is $0.91$, significantly steeper than the 0.6 value predicted by the standard stellar-wind model. Comparing our inferred upper limits to the ionized mass-loss rates deduced from the 6 cm observations with the total mass-loss rates from Knapp (1985) deduced from observations in the CO lines, we can derive upper limits to the “volume-averaged” ionization fractions $f_{\alpha_{\text{ion}}}$ for the winds of these stars (see Table III). For all but two of the stars, we find that $f_{\alpha_{\text{ion}}} \leq 3 \times 10^{-4} - 3 \times 10^{-3}$. For the two exceptions, W Hya and R Hya, we have used total mass-loss rates taken from Gehrz and Woolf (1971), since they were not included in the Knapp (1985) sample, and we consequently infer $f_{\alpha_{\text{ion}}} \leq 1 \times 10^{-4}$. We suspect that the Gehrz and Woolf (1971) values overestimate the total mass loss by about an order of magnitude and hence produce these very low ionization fractions. DL have shown that $f_{\alpha_{\text{ion}}}$ for early M giants and supergiants is $\leq 0.01$, but the present data indicate that the inner portions of the winds or extended chromospheres of late M and C giants and supergiants have lower degrees of ionization by factors of at least 3-30. Judge (1986a,b) determined that ionization of the metals is controlled by Ly$\alpha$ photoionization and that most of the metals are predominately in their first stage of ionization. For solar abundances and complete first ionization of C, Mg, Si, S, Ca, and Fe (ignoring the less abundant metals), $f_{\alpha_{\text{ion}}} = 4 \times 10^{-4}$. Thus the microwave observations of DL indicate that H is partially ionized in the chromospheres of the early M giants and supergiants and of $\alpha^1$ Her (M5 II), while for many of the cool giants in the present survey H is essentially neutral, and the previously mentioned metals (in particular C, the most abundant one) must be the principal sources of free electrons, through their partial or complete first ionization. This is an important result and can be used to place upper limits on the Ly$\alpha$ surface fluxes, which are difficult to measure directly.

It is plausible to associate this large ($\gg 10$) decrease in the average ionization of the inner wind region with the appearance of SiO maser emission, since both phenomena occur at the same spectral type ($\sim M4-M5$). It is difficult at present to make any more quantitative statement based on the radio-continuum data, due to the limited number of detections. One would expect an anticorrelation between, say, the SiO
maser luminosity and the 2 or 6 cm luminosity, but this remains to be proven. More detailed modeling of the thermal conditions in the inner portions of M giant winds, perhaps along the lines suggested by Stencel (1986a,b), would provide a theoretical framework with which to interpret this hypothesis.

The optically thick stellar-wind model is clearly incorrect for several of the observed stars (x Cyg, R Leo, W Hya, and R Hya), since it predicts $\phi_{\text{max}}$ values smaller than the photospheric diameters $\phi_0$, a physical impossibility. In three other cases (R Cas, o Cet, and RX Boo), the upper limit to $\phi_{\text{max}}$ is $<10\%$ greater than $\phi_0$. For these seven stars, we list in Table III(a) the ionized mass-loss rates and fractions for both the optically thick and optically thin stellar-wind models.

The stellar-disk model is also severely constrained for a number of the stars (those with the largest values of $\phi_0$) as the upper limits to the 2 and 6 cm radio fluxes imply low upper limits for the stellar 2 and 6 cm brightness temperatures: $T_e$ (6 cm) $<5200\, \text{K}$ for x Cyg, $<4300\, \text{K}$ for R Leo, $<2500\, \text{K}$ for W Hya, and $<5100\, \text{K}$ for R Hya; and $T_e$ (2 cm) $<3300\, \text{K}$ for o Cet and $<5500\, \text{K}$ for R Cas. These values of $T_e$ are not significantly above the effective temperatures $T_{\text{eff}}$ for these stars (typically $\sim 2000$–$3800\, \text{K}$), and for W Hya the upper limit to $T_e \sim T_{\text{eff}}$. The outer atmospheres of these stars thus must be fundamentally different from stars like the Sun, for which $T_e$ $\sim T_{\text{eff}}$. Any partially or completely ionized region that exists above the photosphere must, therefore, be optically thin at 6 cm.

This result may be used to place constraints on the chromospheric emission measures. The free-free optical depth at centimeter wavelengths is

$$\tau_\nu (\lambda) \approx 1 \times 10^{-22} \lambda^2 \int N_e N_{\text{ion}} T_e^{-3/2} dh,$$  \hspace{1cm} (5)

where we have assumed a value of 5 for the free-free Gaunt factor that is appropriate for $\lambda \sim 6\, \text{cm}$ and $T_e \sim 10^4\, \text{K}$. Two useful quantities are

$$\int N_e N_{\text{ion}} dh \approx T_e^{3/2} \int N_e N_{\text{ion}} T_e^{-3/2} dh,$$  \hspace{1cm} (6)

and

$$\int N_e N_{\text{ion}} dh \approx T_e^{1/2} \int N_e N_{\text{ion}} T_e^{-3/2} dh.$$  \hspace{1cm} (7)

The most stringent constraint on the chromospheres of these stars occurs when $\tau_\nu (6\, \text{cm}) < 1$, which indicates that $\int N_e N_{\text{ion}} T_e^{-3/2} dh < 1.3 \times 10^{26}$. Table IV provides values of $\int N_e N_{\text{ion}} dh$ and $\int N_e N_{\text{ion}} T_e^{-3/2} dh$ for the seven stars with optically thin chromospheres at 6 cm by setting $\tau_\nu (6\, \text{cm}) < 1$, $T_e \approx 6000\, \text{K}$ and using the optically thin value for $f_\text{ion}$ in Table III. These numbers may be compared with upper limits to the emission measure $\int N_e N_{\text{ion}} dh$ for the $\beta$ Gru (M5 III) chromospheric model computed by Judge (1986a). Judge’s model predicts emission measures (essentially determined by the Mg ii flux) $<3 \times 10^{30}$ (above the 5000 K level), $<1 \times 10^{30}$ (above the 6000 K level), and $1 \times 10^{30}$ (above the 7000 K level). The emission measures for the seven stars in Table IV are generally lower than the values for the $\beta$ Gru model, and thus place useful constraints on the amount of ionized material permitted in the chromospheres of these later-type stars.

Our 2 cm detection of R Aql is consistent with this star having a chromosphere as evidenced by its Mg ii emission, but both R Leo and x Cyg have low radio brightness temperatures despite their Mg ii emission. Two possible explanations come to mind:

(i) The chromosphere is cool, with an average temperature $T_e$ below the observed brightness temperature (but above the effective temperature): in the case of R Leo this means $\sim 3 \times 10^3 < T_e < 4.3 \times 10^4\, \text{K}$. This range of temperatures is below that at which Mg ii emission is formed in high-density solar-type chromospheres, but it may be sufficient to produce emission in the low-density, extended chromospheres of red giants, although detailed atmospheric modeling is needed to confirm this, or

(ii) The emission measure or temperature $T_e$ in the chromosphere varies with time, perhaps with the pulsational period of these Mira variables. This interpretation is supported by observations of the carbon star TX Psc (C6.2) (Baumert and Johnson 1984; Johnson et al. 1987) that show that the Mg ii emission flux in this star varies by more than a factor of 8.

The nondetection of o Cet at both 2 and 6 cm in this study despite a previous 3x detection at 6 cm by Spergel et al. (1983) supports the idea that the chromospheres of these late-type giants are variable. (Using the visual light curve shown in Nyman and Olofsson (1985), the Spergel et al. 6 cm observation on 29 October 1981 was made about 57 days past maximum light (equivalent to a phase of 0.16 for the period of 331 days), while our observations on 17 August 1984 were at the later phase of 0.34 (116 days post-maximum)). This well-studied star has a rich ultraviolet emission-line spectrum (Cassatella et al. 1980b) and its outer atmosphere is almost certainly atypical due to the influence of a nearby white dwarf or main-sequence companion (Mira B, unresolved by IUE); the cool wind of the red giant primary is apparently accreting onto the dwarf companion at a rate sufficient to produce a hot accretion shock and a small H ii region. The observed weak x-ray emission (Jura and Helfand 1984) and emission lines, with the possible exception of Mg ii, come from the interaction region and not the red giant wind (Reimers and Cassatella 1985). Our radio-continuum upper limits can be used as independent checks on the pro-

### Table IV. Upper limits to the chromospheric emission measures for stars with chromospheres that are optically thin at 6 cm.

<table>
<thead>
<tr>
<th>Star</th>
<th>Spectral type</th>
<th>Optically thin</th>
<th>$f_{\text{ion}}$</th>
<th>$\int N_e N_{\text{ion}} dh$ (cm$^{-2}$)</th>
<th>$\int N_e N_{\text{ion}} T_e^{-3/2} dh$ (cm$^{-2}$)</th>
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<tbody>
<tr>
<td>x Cyg</td>
<td>S6 + 1/e</td>
<td>yes</td>
<td></td>
<td>$&lt; 1.1 \times 10^{26}$</td>
<td>$&lt; 0.1 \times 10^{30}$</td>
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<tr>
<td>R Cas</td>
<td>M6e-9e</td>
<td>probably</td>
<td>$&lt; 1.9 \times 10^{26}$</td>
<td>$&lt; 1.3 \times 10^{30}$</td>
<td>$&lt; 6.8 \times 10^{30}$</td>
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<tr>
<td>o Cet</td>
<td>M5e-9e</td>
<td>probably</td>
<td>$&lt; 1.7 \times 10^{25}$</td>
<td>$&lt; 1.3 \times 10^{30}$</td>
<td>$&lt; 7.6 \times 10^{30}$</td>
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<tr>
<td>R Leo</td>
<td>M5 III</td>
<td>yes</td>
<td>$&lt; 6.5 \times 10^{25}$</td>
<td>$&lt; 1.3 \times 10^{30}$</td>
<td>$&lt; 2.0 \times 10^{30}$</td>
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<tr>
<td>RX Boo</td>
<td>M5</td>
<td>probably</td>
<td>$&lt; 3.0 \times 10^{25}$</td>
<td>$&lt; 1.3 \times 10^{30}$</td>
<td>$&lt; 4.3 \times 10^{30}$</td>
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<td>W Hya</td>
<td>M5 III</td>
<td>yes</td>
<td>$&lt; 8.3 \times 10^{25}$</td>
<td>$&lt; 1.3 \times 10^{30}$</td>
<td>$&lt; 1.6 \times 10^{30}$</td>
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<tr>
<td>R Hya</td>
<td>M7 III</td>
<td>yes</td>
<td>$&lt; 1.4 \times 10^{25}$</td>
<td>$&lt; 1.3 \times 10^{30}$</td>
<td>$&lt; 9.3 \times 10^{30}$</td>
</tr>
</tbody>
</table>
posed models for the interaction region: they are consistent with the Jura and Helfand (1984) model which predicts a small ($\Delta V \sim 2$ mas) ionized region around Mira B that would be a negligible source of radio emission ($\sim 0.01$ mJy at 2 cm). However, our nondetections strongly disagree with the model of Reimers and Cassatella (1985), which predicts an ionized region ($T_e \sim 10^4$ K) with an emission measure $EM = 2.7 \times 10^{16}$ $cm^{-3}$ (for our adopted distance of 50 pc). The expected optically thin bremsstrahlung at 6 cm from such a region is $\sim 20$ mJy, two orders of magnitude larger than observed. Since $S_6 \propto EM$, the ionized region is constrained by our nondetection to have $EM \leq 3 \times 10^{16}$ $cm^{-3}$, assuming it was unresolved.

V. CONCLUSIONS

We have shown that late M and C giants and supergiants are intrinsically weak radio-continuum sources, despite their stellar winds with large mass-loss rates ($\dot{M} \sim 10^{-7.5}$ to $10^{-6.5} \ M_{\odot}$ yr$^{-1}$). The inferred ionization fractions for the inner wind regions are typically $<0.0003$--0.003, an order of magnitude or more smaller than those of earlier M supergiants like $\alpha$ Ori and $\alpha$ Sco. The only convincingly detected source is R Aql, a 3$\sigma$ source at 2 cm. There is a radio source near ($7''$, $15''$) the optical/infrared positions of R Cas and AFGL 865, but we cannot associate it with the optical or infrared object at this time.

We have obtained brightness temperatures at 2 and/or 6 cm for several stars that are $\sim 5 \times 10^3$ K with the most extreme value being $T_b < 2.5 \times 10^3$ K for W Hya, at 6 cm. This implies that in at least some red giants, chromospheres are either absent or contain so little ionized gas that their optical depth at centimeter wavelengths is $\leq 1$, implying that $\int N_e \sigma T_e dh < 10^{26}$ cm$^{-5}$.

We recommend that future radio-continuum studies of these and similar stars be made at 2 cm or millimeter wavelengths since these stars appear to have rather steep spectral indices ($\gamma \gtrsim 1.0$). The optimum VLA wavelength is probably 2 cm: for $T_b \sim T_{eff} \sim 3 \times 10^3$ K and a 2 cm detection threshold of 0.3 mJy, all stars with $\phi \gtrsim 28$ mas should be detected. We predict that $\chi$ Cyg, $\sigma$ Cet, R Leo, W Hya, and R Hya (and possibly R Cas and RX Boo) should be 2 cm sources above this level. We also recommend that any stars detected as radio-continuum sources (such as R Aql) be monitored, since there is evidence that these stars are variable radio sources, and it is important that the timescale of such variability be determined in order to constrain better the physical dimension of the emission region(s).

We would like to acknowledge the financial support of the National Aeronautics and Space Administration through grant no. NGL-06-003-057 to the University of Colorado and the National Science Foundation through grant no. AST-830495 to the University of Kentucky. We are also grateful for the assistance and advice of the VLA technical and scientific staff.

REFERENCES

Johnson, H. R., Baumeier, J. H., Querci, F., and Querci, M. (1987). As-
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1987AJ 94.1280D