RADIO EMISSION FROM HOT STARS AT TWO CENTIMETERS

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Radio fluxes of 7.2 ± 1.1 and 69 ± 5 mJy at 14.7 GHz have been detected from the stars ζ Pup (O4If) and γ Vel (WC8+O9I) respectively with the 64-m telescope at Parkes, and upper limits have been determined for 9 more hot stars. The interpretation of these fluxes as free-free emission from a shell of ionized gas resulting from a stellar wind gives mass-loss rates $\dot{M} = (6.5 \pm 1.4) \times 10^{-6}$ $M_\odot$ yr^{-1} for ζ Pup and $(3.9 \pm 0.7) \times 10^{-5}$ $M_\odot$ yr^{-1} for γ Vel if H/He = 10 by number and the He is fully ionized. If the gas around γ Vel originates mainly from the WC8 star, the helium predominates and $\dot{M} = (5.2 \pm 0.9) \times 10^{-5}$ or $(17 \pm 3) \times 10^{-5}$ $M_\odot$ yr^{-1} depending on whether the helium is doubly or singly ionized.

1. INTRODUCTION

The mass ejected by a hot star will form an expanding shell of ionized gas emitting bremsstrahlung which may be observable at radio and infrared wavelengths. Thus, the radio fluxes detected from P Cyg by Wendker, Baars and Altenhoff (1973) and from the Wolf-Rayet binary γ Vel by Seaquist (1976) probably originate from stellar winds. Similarly, the infrared excesses that Barlow and Cohen (1977) found at 10 μm in several hot supergiants can be explained by the same model.

In a previous paper (Morton and Wright 1978, Paper I) we described the first measurement of radio emission from ζ Pup and additional radio data on γ Vel. In this paper we report further observations of these stars, upper limits for 9 more hot stars, and a re-analysis of γ Vel for the case of a helium-rich atmosphere. The observations were made with the Parkes 64-m radio telescope. A high frequency is very useful for such a programme because the radio flux density S_ν is approximately proportional to $\nu^{0.6}$ in the mass-loss model, while the background confusion is less than at lower frequencies due to the narrower telescope beam and the spectra of the contributing sources.

In several ways the radio flux provides valuable information about stellar mass ejection. First, the radio emission, which arises from all

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Table 1. Radio Flux Densities at 14.7 GHz.

Star	b	Date	No. of runs	Flux S_ν (mJy) Observed	Flux S_ν (mJy) Adopted
ζ Pup	-4° 42'	1977 Jun	7	6.7 ± 1.5	7.2 ± 1.1
		1977 Nov	9	7.5 ± 1.2	
γ Vel	-7° 41'	1977 Jun	4	67 ± 5	69 ± 5
		1977 Jun	scan	70 ± 10	
		1977 Nov	3	77 ± 7	
		1978 May	3	67 ± 7	
		1978 May	scan	65 ± 8	
θ Mus	-2° 29'	1977 Jun	1	-0.9 ± 3.0	<7
HD 151804	+1° 57'	1977 Jun	1	-0.4 ± 3.4	<5
		1978 May	1	0.8 ± 1.7	
HD 152408	+1° 30'	1977 Jun	3	2 ± 14	<5
		1977 Nov	1	-3 ± 3	
		1978 May	1	2.2 ± 1.7	
HD 112244	+6° 02'	1977 Jun	1	0.4 ± 2.6	<7
δ Ori	-17° 45'	1977 Jun	1	-2.5 ± 3.5	<7
ε Ori	-17° 15'	1977 Jun	1	-1.0 ± 3.2	<7
ρ Leo	52° 46'	1977 Jun	1	-0.5 ± 6.0	<12
ζ^1 Sco	+0° 53'	1977 Jun	3	14 ± 5	<10
		1977 Nov	1	10 ± 4	
		1978 May	1	4 ± 6	
		1978 May	scan	10	
η Cen	+16° 41'	1977 Jun	1	0.8 ± 3.4	<7

ionized species including hydrogen and helium, can be a useful check on the mass-loss rate obtained from ultraviolet or visual line profiles, where the results may be highly sensitive to estimates of the ionization equilibrium. Secondly, it may be possible to combine the data with information at other wavelengths to obtain constraints on the temperature and velocity law in the outer parts of the stars. Thirdly, since the radio emission originates over a larger radial extent, time variations are not as important as at infrared and shorter wavelengths. Also, as discussed by Wright and Allen (1978), when an ejection event does occur, it is expected to appear first at optical frequencies and later in the infrared and radio regimes as the material moves outwards.

2. OBSERVATIONS

Three separate observing runs were made with a new 14.7 GHz cryogenic, parametric receiver on the Parkes 64-m radio telescope (see Paper I). At this frequency, only the 37-m centre section of the dish is illuminated. The receiver had two beams of 2.3 arcmin half power width, one on axis and the other 6.2 arcmin off axis. Usually the telescope was operated in the wagging mode (Wright 1974) in which the feed was rotated to align the two beams to the same zenith angle, and then the telescope was moved so that alternate beams were pointed at the source, with typical cycle times of 30 sec. Table 1 lists the sources, galactic latitude b, dates, and flux densities. In some cases a star was chosen more for zenith angle than being a candidate for strong radio emission. The periods of observation were 1977 Jun 20-24, 1977 Nov 22-29, and 1978 May 5-8 when the receiver was tuned to 14.7, 14.45 and 14.4 GHz respectively. For simplicity we have adopted 14.7 GHz for all the analysis. Sources were observed one or more times with runs of wags ranging from 8 to 40, depending on the stability of the signal. Cirrus cloud in the far-field of the telescope can add considerable noise at 2 cm. The number of such separate runs is noted in column 4 of Table 1. Scans in α and δ also were made on γ Vel and ζ^1 Sco with scan lengths of about ± 10 arcmin. Finally, the tables list our best judgement of the flux density and rms error, or a conservative upper limit.

ζ Pup: Resonable signals above the noise were obtained from ζ Pup on two separate occasions. Observations at positions 15 and 2 arcmin off the source gave signals comparable with the noise, showing that the region is not seriously confused by other sources. We consider that the detection of ζ Pup is highly probable and adopt $S_\nu = 7.2 \pm 1.1$ mJy at 14.7 GHz. This is the weakest source yet measured by the Parkes telescope at any frequency.

γ Vel: A strong signal was observed from γ Vel, as expected from the measurements by Seaquist (1976) at lower frequencies. Scans across the source gave a peak in good positional agreement with the Wolf-Rayet binary. The three separate observing sessions give consistent results so that we adopt $S_\nu = 69 \pm 5$ mJy. The suggestion of variation in Paper I was due to one measurement in May 1977 which we now know to be incorrect.

ρ Leo: The run suffered from thin, cirro-stratus cloud near sunset, making the limit abnormally high.

ζ^1 Sco: On the first two occasions, ζ^1 Sco seemed close to detection, but the results were not confirmed in May 1978. Observations a few arcmin off the source imply the presence of other emission of similar strength within 3 arcmin. We suspect that ζ^1 Sco is indeed a source of about 9 mJy, but the detection above the background is not clear, unlike ζ Pup which is farther from the galactic equator. Thus we adopt the limit $S_\nu < 10$ mJy.

3. ANALYSIS

Wright and Barlow (1975) and Panagia and Felli (1975) have derived simple relations between the rate of mass loss $\dot{M}$ and radio flux density S_ν at frequency ν when the flow is uniform and spherically symmetric with a velocity V_∞ independent of radius and time. The majority of the radio emission should originate far from the star so that the velocity can be approximated by the terminal value. The Wright-Barlow formulation gives

$$\dot{M} = \frac{0.095\ \mu V_\infty\ S_\nu^{3/4}\ D^{3/2}}{Z\ \gamma^{\frac{1}{2}}\ g^{\frac{1}{2}}\ \nu^{\frac{1}{2}}}\ M_\odot\ \mathrm{yr}^{-1}$$

with V_∞ in km s^{-1}, S_ν in Jy, ν in Hz and D the distance in kpc. The remaining parameters depend on the composition, kinetic temperature T, and ionization equilibrium in the radiating gas. Specifically, μ is the mean atomic weight per nucleon, γ is the number of electrons per ion, and Z is the rms average charge of the ions. In each case it is necessary to sum over all elements weighing each by its abundance, though in practice only hydrogen and helium are important unless both are depleted relative to the heavies. Finally, g is the Gaunt factor for which we use Spitzer's (1962) approximation for radio waves

$$g = \frac{3^{\frac{1}{2}}}{\pi}\left[\ln \frac{(2kT)^{3/2}}{\pi Z e^2 \nu m_e^{\frac{1}{2}}} - 1.443\right]$$

There is considerable debate whether the temperature in the wind from a hot star is close to the effective temperature or near 2×10^5 K. This high value was found in ζ Pup by Lamers and Morton (1976) and in τ Sco (B0V) by Lamers and Rogerson (1978), due to the presence of N V and particularly O VI P-Cygni profiles. Both N V and O VI also occur in ζ Pup, γ Vel, δ Ori, ε Ori and HD 152408 and at least N V is present in ρ Leo, HD 112244, θ Mus and HD 151804 according to the observations of Morton (1976, 1978), Snow and Morton (1976), Hutchings (1976b) and Johnson (1978). Both ions seem to be absent in η Cen and the status of ζ^1 Sco is not yet known. Thus we have adopted $T = 2.5 \times 10^4$ for η Cen, and 2×10^5 for all others. In the case of ζ Pup, if we had taken $T = 5 \times 10^4$ there would be only a 20% reduction in g, but γ and Z would change by larger amounts due to the helium not being fully ionized. A range of possibilities for the parameters μ, γ, Z and g is listed in Table 2. In normal stars, H/He $\simeq$ 10 by number, but H/He = 1 or 0.1 is probably more appropriate for a Wolf-Rayet star (Smith 1973). The small effect of the cosmic abundances of the heavier elements has been included. Either decreasing T from 2×10^5 to 2.5×10^4 K or making helium the dominant element increases $\dot{M}$ by at most 40%, but changing both so that the main source of electrons is singly ionized helium can increase $\dot{M}$ by more than a factor 4.

Table 2. Effects of Changing the Adopted Temperature and Helium Abundance.

T	2×10^5	2×10^5	5×10^4	2.5×10^4	2.5×10^4
H/He	10	0.1	10	10	0.1
γ(He)	2	2	2	1	1
μ	1.3	4.1	1.3	1.3	4.1
γ	1.1	2.0	1.1	1.0	1.0
Z	1.13	2.0	1.13	1.0	1.02
$g(\nu = 14.7 \times 10^9)$	6.9	6.6	5.7	5.2	5.2
$\frac{\mu}{Z \gamma^{1/2} g^{1/2}}$	0.42	0.56	0.46	0.57	1.76
ratio	1	1.3	1.1	1.4	4.2

Table 3 lists the adopted parameters for each star and the derived mass-loss rate or its upper limit. In most cases the spectral types, distances and terminal velocities are the same as used by Snow and Morton (1976). For γ Vel we adopted the spectrum derived by Conti and Smith (1972), the distance of ζ Pup, and the terminal velocity from the C IV line plotted by Johnson (1978). The spectrum and distance of θ Mus are from Moffat and Seggewiss (1977), and the terminal velocity from N V as quoted by Hutchings (1976b). Since ζ^1 Sco appears to be associated with the cluster containing HD 151804 and 152408, the same distance was used for all three stars. The spectral type of ζ^1 Sco is from Lesh (1972) and the terminal velocity from the C IV P-Cygni profile observed with the International Ultraviolet Explorer. We have revised the velocity for HD 151804 slightly to include new data on O VI and we have adopted values for δ and ε Ori from Abbott (1978) who ignored the N V extreme short wavelength wing which may be due to a blend.

The mass-loss rates are listed in the last row of Table 3. For the two Wolf-Rayet systems it was assumed that the WR star is the prime contributor to the wind and hence the helium is the main constituent. Since the nitrogen is ionized 4 times in the wind, the helium should be fully ionized. However, we cannot rule out the possibility of helium recombination farther out where the radio emission originates or Auger ionization of the heavier elements by a corona at $7 \approx 10^6$ K leaving the helium singly ionized. If so, a considerable correction must be applied as shown by Table 2. The quoted error on $\dot{M}$ does not include this possibility, so that the distance is the major source of uncertainty.

Table 3. Mass-Loss Rates Based on Observations at ν = 14.7 GHz.

Star	ζ Pup	γ Vel	θ Mus		
HD	66811	68273	113904	151804	152408
Spectrum	O4If	WC8 +O9I	WC6 +O9.5I	O8Iaf	O8:Iafpe
D (kpc)	0.45	0.45	2.0	2.2	2.2
S_ν (mJy)	7.2±1.1	69±5	< 7	< 5	< 5
V_∞ (km s^{-1})	2660 ±150	2900 ±150	1650	1700	1430
T	$2\text{x}10^5$	$2\text{x}10^5$	$2\text{x}10^5$	$2\text{x}10^5$	$2\text{x}10^5$
H/He	10	0.1	0.1	10	10
γ(He)	2	2	2	2	2
$\frac{\mu}{Z\,\gamma^{\frac{1}{2}}\,g^{\frac{1}{2}}}$	0.42	0.56	0.56	0.42	0.42
$\dot{M}(10^{-6}\ M_\odot\ yr^{-1})$	6.5 ±1.4	52 ±9	<50	<34	<29

Star		δ Ori	ε Ori	ρ Leo	ζ^1 Sco	η Cen
HD	112244	36486	37128	91316	152236	127972
Spectrum	O8.5Iab	O9.5II	B0Ia	B1Iab	B1.5Ia+p	B1.5V
D (kpc)	1.5	0.46	0.46	1.0	2.2	0.10
S_ν (mJy)	<7	<7	<7	<12	<10	<7
V_∞ (km s^{-1})	1900	2410	2010	1580	950	810
T	$2\text{x}10^5$	$2\text{x}10^5$	$2\text{x}10^5$	$2\text{x}10^5$	$2\text{x}10^5$	$2.5\text{x}10^4$
H/He	10	10	10	10	10	10
γ(He)	2	2	2	2	2	1
$\frac{\mu}{Z\,\gamma^{\frac{1}{2}}\,g^{\frac{1}{2}}}$	0.42	0.42	0.42	0.42	0.42	0.57
$\dot{M}(10^{-6}\ M_\odot\ yr^{-1})$	<28	<6.0	<5.0	<19	<32	<0.28

4. DISCUSSION

The rate of mass loss for ζ Pup is in excellent agreement with $\dot{M} = (7 \pm 3) \times 10^{-6}$ $M_\odot$ yr^{-1} which Lamers and Morton (1976) derived from the far-ultraviolet line profiles and 8×10^{-6} $M_\odot$ yr^{-1} which Cassinelli, Olson and Stalio (1978) obtained from the Hα profile even though the UV analysis led to $T = 2 \times 10^5$ K and the Hα gave best agreement at $T \approx 3 \times 10^4$ K. To confirm the radio result it would be good to measure ζ Pup at another frequency to check that $S_\nu \propto \nu^{0.6}$.

In the case of the Wolf-Rayet binary γ Vel, our best estimate of 5.2×10^{-5} $M_\odot$ yr^{-1} is significantly below 9×10^{-5} $M_\odot$ yr^{-1} that Willis and Wilson (1978) derived from the C III] λ1909 absorption line, or 2.7×10^{-4} that Barlow and Cohen (1978) obtained from the IR excess. If we had adopted their assumption that helium is singly ionized, our $\dot{M}$ would increase to 1.7×10^{-4} $M_\odot$ yr^{-1}. Presumably, the rest of the discrepancy is due to the acceleration that is occurring in the region of infrared emission, as discussed by Barlow and Cohen (1978).

For the extremely luminous supergiants 151804, 152408 and ζ^1 Sco, Hutchings (1968) estimated mass-loss rates $\dot{M}$ of 1×10^{-5}, 1×10^{-4} and 1×10^{-5} $M_\odot$ yr^{-1} respectively from the visible P-Cygni lines. Our upper limits are consistent for 151804 and ζ^1 Sco, but show that Hutchings' value is too high for 152408. Barlow and Cohen (1977) obtained 1.4×10^{-5} $M_\odot$ yr^{-1} from the IR excess in ζ^1 Sco, but they assumed $V_\infty = 500$ km s^{-1}. Increasing the terminal velocity to 950 km s^{-1} determined from the C IV resonance absorption gives $\dot{M} = 2.7 \times 10^{-5}$ consistent with our suspicion that $S_\nu \approx 9$ mJy.

In δ Ori and ε Ori our upper limits on $\dot{M}$ are consistent with 1.0×10^{-6} and 1.7×10^{-6} $M_\odot$ yr^{-1} respectively, estimated by Morton (1967) from the UV P-Cygni absorptions and 0.9 and 1.7×10^{-6} found by Barlow and Cohen (1977) using the IR excess. Our limit on ρ Leo is well above 8.6×10^{-7} $M_\odot$ yr^{-1} that these authors obtained and our limit for η Cen is consistent with 7×10^{-9} $M_\odot$ yr^{-1} that Lamers and Rogerson (1978) derived from the UV P-Cygni lines in τ Sco (B0V).

For the remaining stars HD 112244 and θ Mus our upper limits agree with the rough estimates of 5×10^{-6} and 8×10^{-6} $M_\odot$ yr^{-1} respectively by Hutchings (1976a, b), who compared the mass-loss features in their visible and UV spectra with stars for which $\dot{M}$ had been determined. His standards included HD 152408, which we believe has been overestimated, and P Cyg itself, which now seems to be highly abnormal.

Our observations imply that for most OB stars, including the extreme supergiants 151804, 152408 and ζ^1 Sco, $\dot{M} < 5 \times 10^{-5}$, and that WC stars have the same limit (or possibly a factor 3 larger if the helium is mainly singly ionized). Therefore, if the radio flux is to be detectable easily with an antennae the size of Parkes, the star will have to be closer than ~ 500 pc. Thus, stars worth observing include ξ Per

(O7.5III), λ Ori (O8III), ι Ori (O9III), ζ Oph (O9.5V), ζ Ori (O9.7Ib) and ζ Per (B1Ib). Otherwise it will be necessary to use interferometric techniques to distinguish the weak point sources from the background.

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DISCUSSION FOLLOWING MORTON AND WRIGHT

Cassinelli: What temperature did you assume in your derivation of $\dot{M}$ and what would be the effect of changing T from 2×10^5 to 3×10^4 or vice versa?

Morton: Since O VI is present, we used 2×10^5°K. Decreasing to 3×10^4°K has little effect on $\dot{M}$, provided the helium remains fully ionized.

Underhill: How do you know that the radio emission comes from the gas that produces the O VI?

Morton: The radio emission probably originates further out than the O VI, but I doubt that any recombination has occurred.

Niemela: I'd like to ask whether γ Vel B may contribute to the radio emission from γ Vel A? γ Vel B is also a binary star which Dr. Sahade is working on. There are radio observations from binaries ... .

Barlow: The known radio binaries usually don't have a $\gamma^{2/3}$ spectrum. Their radio spectra look nonthermal and so can be distinguished that way.

Hutchings: The revised $\dot{M}$ rates I gave yesterday, which agree with Barlow and Cohen's values, are ~2 times lower in the range occupied by ζ^1Sco, 152408, 151804 and they also fit in well with your upper limits.

Kwok: What velocities did you use for γ Vel?

Morton: I used 2900 km s^{-1} from the C IV line plotted by H. Johnson (Ap. J. 1978). The other values were from the UV mass loss survey (Snow and Morton 1977).