RADIO EMISSION FROM WR STARS

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In principle radio observations of WR stars offer the best possibility of determining the rate of mass loss, since for a simple model of the extended atmosphere the mass loss rate depends primarily on quantities--the flux density, the velocity, and the distance--which are observable (Barlow 1979). Until now, detections of Wolf-Rayet stars have been limited by the sensitivity and resolution of available telescopes. The advent of the Very Large Array makes a search for emission from a large number of these stars feasible.

The VLA has been used in two observing periods to study nine WR stars. In the first period the observations were concentrated on four stars associated with symmetric nebula, on the assumption that such stars might have favorably high mass loss rates. In the second period the search was extended to five additional stars. The results are summarized in Table 1.

TABLE 1. FLUX DENSITIES AND IMPLIED MASS LOSS RATES

Object	Type	Epoch	Frequency (GHz)	Flux (mJy)	Mass Loss (10^{-5} $M_\odot$ yr^{-1})
HD 190918	WN 4+09I	1981.0	4.9	< 0.3	< 2
HD 50896	WN 5	1980.1	4.9	1.06	
		1981.0	4.9	1.01	3.0
		1981.0	15.0	2.25	3.2
HD 56925	WN 5	1980.1	4.9	< 0.2	< 6
HD 191765	WN 6	1980.1	4.9	0.81	
		1981.0	4.9	0.76	2.7
		1981.0	15.0	2.15	3.8
HD 151932	WN 7	1981.0	4.9	1.30	4.4
HD 214419	WN 7+07	1981.0	4.9	< 0.15	< 4
MR 97	WN 7	1980.1	4.9	< 0.15	< 0.3
HD 152270	WC 7+05	1981.0	4.9	1.15	5.0
HD 192103	WC 8	1981.0	4.9	0.60	2.3

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Before mass loss rates can be computed from the observed radio fluxes, it is necessary to estimate some atomic parameters of the wind. Considerable controversy surrounds the hydrogen abundance, with estimates ranging from little hydrogen (Smith 1973) to normal hydrogen abundance (Underhill 1980). I adopt a ratio by number of H/He << 1 for stars of type WN 4, and WN 5, and WC, and H/He ~ 1 for stars of all other types. An uncertainty also arises in the ionization state of the atmosphere in the radio-emitting region. I assume that $He^{++}/He^{+} \gg 1$ for stars of type WN 4-6 and WC; for all others I adopt $He^{++}/He^{+} \sim 1$.

With these assumptions, and using values of the distance and wind velocity primarily from Barlow, Smith, and Willis (1981), the rates of mass loss are calculated in the usual way (cf. Barlow 1979), and are shown in Table 1. The range in mass loss rates is small, in agreement with the results of Barlow et al. obtained from a large body of infrared data. A notable exception is MR 97, which has a rate at least a factor of ten smaller than the WN 7 star HD 151932.

The mean spectral index between 10 μm and 6 cm is 0.76 ± 0.02, exactly the value adopted by Barlow et al. in their derivation of mass loss rates from infrared fluxes. The deviation of the index from the value 0.6 expected for a spherical nebula expanding at constant velocity presumably arises because the material in the infrared region has not attained the terminal velocity. The small range observed for this index implies that the ratio of velocities in the infrared and radio regions is approximately constant, even though the detected stars span a wide range of spectral type.

The formal uncertainty in the estimate of mass loss rates is perhaps forty percent, and is dominated by the uncertainty in the distance. Potentially more serious however are the uncertainties in the model atmosphere. These are:

1. For a wind dominated by He^{+}, the mass loss rate will be underestimated by a factor of up to 2.7. The constancy of the 10 μm - 6 cm spectral index suggests this effect is not important.

2. If the wind is concentrated in an equatorial plane, the mass loss rate is overestimated by a factor which depends upon the orientation and thickness of the disk. For example, the factor is 2.7 for a disk of opening angle 20 degrees viewed pole-on. Since the spectral index of the radio emission from a disk is the same as that of a sphere, if the flow is at constant velocity, this geometric effect can be studied only by direct measurement of the shape of the radio emitting region, using long baseline interferometry. This observation is difficult at the sensitivities now available.

3. If the wind is variable in time the radio properties differ from the simple case (Abbott, Bieging, and Churchwell 1981). Both the total flux and the spectral index are useful indicators of such

activity. Neither HD 50896 nor HD 191765 showed any significant change in flux density at 6 cm between the two observing periods, and indeed the spectral index for HD 50896 (0.7 ± 0.2) is consistent with a constant mass loss rate. The spectral index of HD 191765 (0.9 ± 0.2) is perhaps steeper than expected, and it will be useful to monitor the flux density of this star.

If the rates of mass loss of the WR stars found in this program are typical, the VLA is capable of detecting radio emission from WR stars lying at distances of up to 5 kpc.

REFERENCES

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DISCUSSION

Abbott: Infrared observations of MR97 by myself, Charles Telesco and Sydney Wolff indicated that the published E_{b-v} is too large, which helps eliminate the $\dot{M}$ discrepancy for this star. I don't think it is likely that the ionization of He could change drastically between the radii observed in the optical and UV and that observed in the radio, because very little optical depth of the wind occurs in this region.

Cassinelli: It is interesting that you have pointed out another important fact that we must consider in modelling WR winds, i.e. that α = 0.76-0.78 from 10μ to 6cm. This suggests that the velocity law is the same in the outer regions for all WR stars. Not only are the stars throttled to the same $\dot{M}$, but also to the same v(r) beyond where $\tau(10\mu) \sim 1$. Your comment that the $\dot{M}$ would be changed if the helium were not doubly ionized throughout may be related to Panagia's discussion earlier. He found that to keep the gas fully ionized the effective temperatures must be closer to 60000K rather than the 30-40000K that we have been hearing about from UV colour measurements. Would Nino care to comment on this ?

Panagia: The double ionization of He requires the radiation temperature to be about 60000K for $\lambda < 228$ Å. This temperature may not be quite appropriate for the whole far UV spectrum but surely provides a clear indication that the emission in the Lyman continuum ($\lambda < 912$ Å) is much higher than expected on the basis of the colour temperature measured in the optical and the near UV. At any rate, since most of the emission measure of the wind is at the base of the flow the doubly ionized helium region is either limited to very next to the stellar surface or extends practically up to an infinite distance (cf Felli and Panagia, 1981, Astron. Astrophys., 102, 424).

Hogg: I was worried about the ionization state of helium because of the colour temperature problem. If another source of energy is available such as was described in the review by Cassinelli, how will the ionization state at some distance from the star be affected ? However, I agree with your argument that it is unlikely that helium recombines between the infrared and radio regions.

Lundstrom: The identification of MR97 has been uncertain up to very recently. It might be that photometry quoted in the van der Hucht et al. catalogue in fact refers to a nearby non-WR star.

Hogg: It is important to get an accurate distance for MR97, in order to see if the mass loss rate is as low as it now appears to be.