RADIO CONTINUUM MEASUREMENTS OF MASS LOSS FROM WOLF-RAYET STARS

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I. INTRODUCTION

The Wolf-Rayet phenomenon is defined by the striking emission line spectrum which is observed at UV, optical, and IR wavelengths. The usual interpretation is that this characteristic emission-line spectrum results from a stellar wind which has such a high density that even relatively weak lines are formed in the extended envelope formed by the outflow. This model leads to the expectation that the Wolf-Rayet phenomenon is linked to stars which have very high rates of mass loss. The purpose of this paper is to examine the relationship between the mass loss rate and the spectral appearance of O, Of, and WR stars.

II. OBSERVED MASS LOSS RATES

Measurements of free-free emission at radio wavelengths provides a nearly model-independent estimate for the mass loss rates of early-type stars (e.g. Barlow 1979). We observed the 15 WR stars listed in Table 1 at 4885 MHz using the NRAO[1] Very Large Array, and detected radio emission from 10 stars. A detailed discussion of the observations will be given by Bieging, Abbott, and Churchwell (1982).

[1]The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract with the United States National Science Foundation.

C. W. H. de Loore and A. J. Willis (eds.), Wolf-Rayet Stars: Observations, Physics, Evolution, 215–220.

Table 1. Derived Mass Loss Rates

Star	Sp. T[a]	S_{4885} (mJy)	D (kpc)	v_∞ (km s^{-1})	C_1 [b] ($\times 10^{-7}$)	$\dot{M}$ (10^{-5} $M_\odot$ yr^{-1})
HD 4044	WN5	0.47	(2.5)	(2300)	8.4	2.4
V444 Cyg	WN5+O	0.28	(2.1)	2500	8.4	1.4
HD 193077	WN5+abs	0.60	((1.5))	1700	8.4	1.0
MR 111	WN-C	0.98	2.0	(2400)	(8.4)	3.2
HD 165688	WN6	0.96	(1.8)	(2200)	8.4	2.4
HD 151932	WN7	(1.25)	2.1	2250	9.0	4.1
AS 374	WN8	<0.20	((2.6))	(1400)	9.3	<0.9
MR 110	WC5	0.67	2.0	(2800)	8.4	2.8
HD 16523	WC5	<0.20	(3.9)	2800	8.4	<3.0
HD 165763	WC5	0.33	(2.6)	2800	8.4	2.4
HD 190002	WC6	<0.20	((1.8))	(2600)	8.4	<0.9
HD 192641	WC7+abs	0.37	(1.7)	(2600)	(8.4)	1.3
HD 152270	WC7+O	(0.20)	2.1	3300	(8.4)	<1.4
CV Ser	WC8+O	⩽0.41	2.0	(1800)	12.0	⩽1.8
AS 320	WC9	<0.30	((2.8))	(2200)	12.0	<2.8

[a] van der Hucht et al. (1981).

[b] $C_1 \equiv 0.095\ \mu/z(\gamma g \nu)^{0.5}$.

The stars in Table 1 cover nearly all spectral types of both the WN and WC sequence. Stars of particular interest are the hybrid WN-C star, MR 111; two stars with "intrinsic" absorption lines of hydrogen, HD 193077 and HD 192641; and three known (WR+O) systems. The derived mass loss rates depend on the values of the radio flux, the terminal velocity, the distance to the star, and the chemical composition and ionization state of the wind. Parentheses in Table 1 denote added uncertainty for one of these values.

All detected stars have mass loss rates in the interval $1.0 \times 10^{-5} \leqslant \dot{M} \leqslant 4.0 \times 10^{-5}\ M_\odot\ yr^{-1}$. This is quite remarkable, considering that the stars span a large range in temperature, mass, luminosity, emission-line strength, duplicity, and chemical composition. This indifference of the mass loss rate to the properties of the underlying star is shown in figure 1, where we have also plotted radio mass loss rates from Dickel et al. (1980), Hogg (1981), and Seaquist (1976). The left panel shows that the mass loss rates of Wolf-Rayet stars are: (1) much larger than those of OB stars of comparable luminosity; and (2) uncorrelated with bolometric luminosity. The error bar shows the range of uncertainty in $\dot{M}$ resulting from a factor of 2 uncertainty in the distance. The values of L_{bol} are from Barlow, Smith, and Willis

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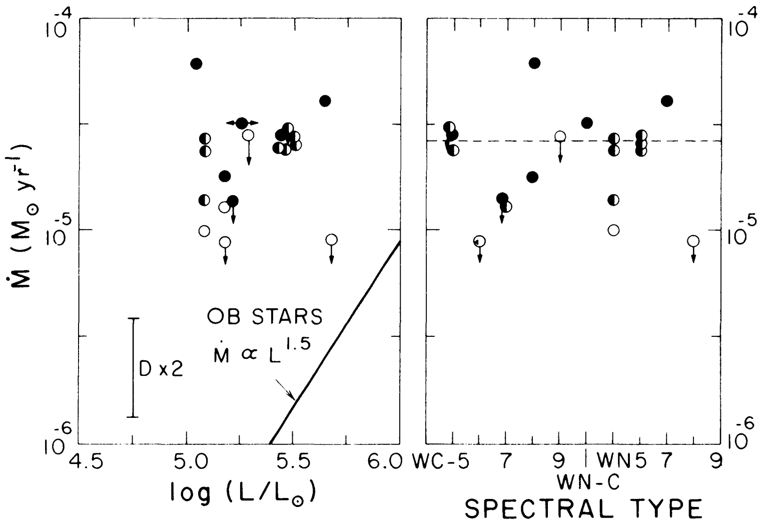

Figure 1. The dependence of mass loss rate on bolometric luminosity (left panel) and spectral type (right panel). Filled circles are stars with distances based on cluster membership. Half-filled circles are stars with distances based on the M_V calibration of van der Hucht et al. (1981), and reliable E(B-V). Open circles are stars with distances as above but E(B-V) is uncertain. Solid line in left panel is a least-squares fit to VLA observations of OB stars by Abbott, Bieging, and Chuchwell (1981).

(1981), and are also uncertain by typically ±0.3 dex, so a weak correlation between $\dot{M}$ and L is not detectable by these observations.

The complete lack of dependence of $\dot{M}$ on spectral type is shown in the right panel of figure 1. The dashed line is the mean mass loss rate of all WR stars, $\langle\dot{M}\rangle = 2.6(\pm 1.3) \times 10^{-5}\ M_\odot\ yr^{-1}$. The standard deviation of ±50% is of the same order as the observational uncertainty in $\dot{M}$, so our data are consistent with identical mass loss rates for all Wolf-Rayet stars.

III. THE O, Of, AND WR STAR CONNECTION

This result raises a fundamental question about the Wolf-Rayet phenomenon, which so far has not been addressed at this symposium. That is, we know that Wolf-Rayet stars are defined observationally by their emission-line spectrum. But, what are the properties of these stars that cause such spectacular emission? The standard explanation -- mass loss -- is obviously an element. However, the fact that stars

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with very dissimilar spectra can have identical mass loss rates suggests that there is more to the explanation.

The situation becomes even more extreme when viewed within the context of mass loss from all early-type stars. Figure 2 shows a sequence of stars of spectral type O V → O III → O Ib → Of → WN → WC. Presumably, each star in the sequence is at a more advanced stage of evolution than the star above it. The mass loss rates given for each star are from VLA radio measurements at λ6 cm, and they are all nearly identical. The O-type stars also have similar luminosities, while those of the WR stars are smaller. Also shown are the infrared excess emission from Abbott et al. (1982b), line profiles of the He II 4686 spectral region from Conti and Frost (1976) and Smith and Kuhi (1981), and IUE low-resolution spectra from Conti and Garmany (1981, unpublished).

We conclude from figure 2 that the emission strength -- be it measured from optical lines, infrared free-free, or the ratio of emission to absorption in UV P-Cygni profiles -- does not correlate with the mass loss rate. There must exist one, or more, other factors that combine with mass loss to produce the Wolf-Rayet, and to a lesser extent the Of, phenomenon. A clue to the identity of this other factor is the strong correlation between the emission strength and the evolutionary state of the star, which is apparent in figure 2. By this, we do not mean that the emission lines are linked to processes occurring in the interior. Rather, we suggest that as a star evolves, the variation in its mass, radius, chemical composition, scale height, etc. cause changes in the structure of the atmosphere and wind, which strengthen the emission measure of the envelope. For example, there is evidence that supergiant OB stars have a more gradual velocity law v(r) than main sequence OB stars (Abbott, Bohlin, and Savage 1982a). From the equation of continuity, $\rho(r) = \dot{M}/(4\pi r^2 v)$, this means that the supergiants have a higher density envelope than main sequence stars with the same rate of mass loss.

To summarize, our observations show that there is an empirical link between the emission strength and evolutionary state of O and WR stars, which is independent of the mass loss rate. Until this link is explained, our understanding of the origin of the Wolf-Rayet phenomenon remains incomplete.

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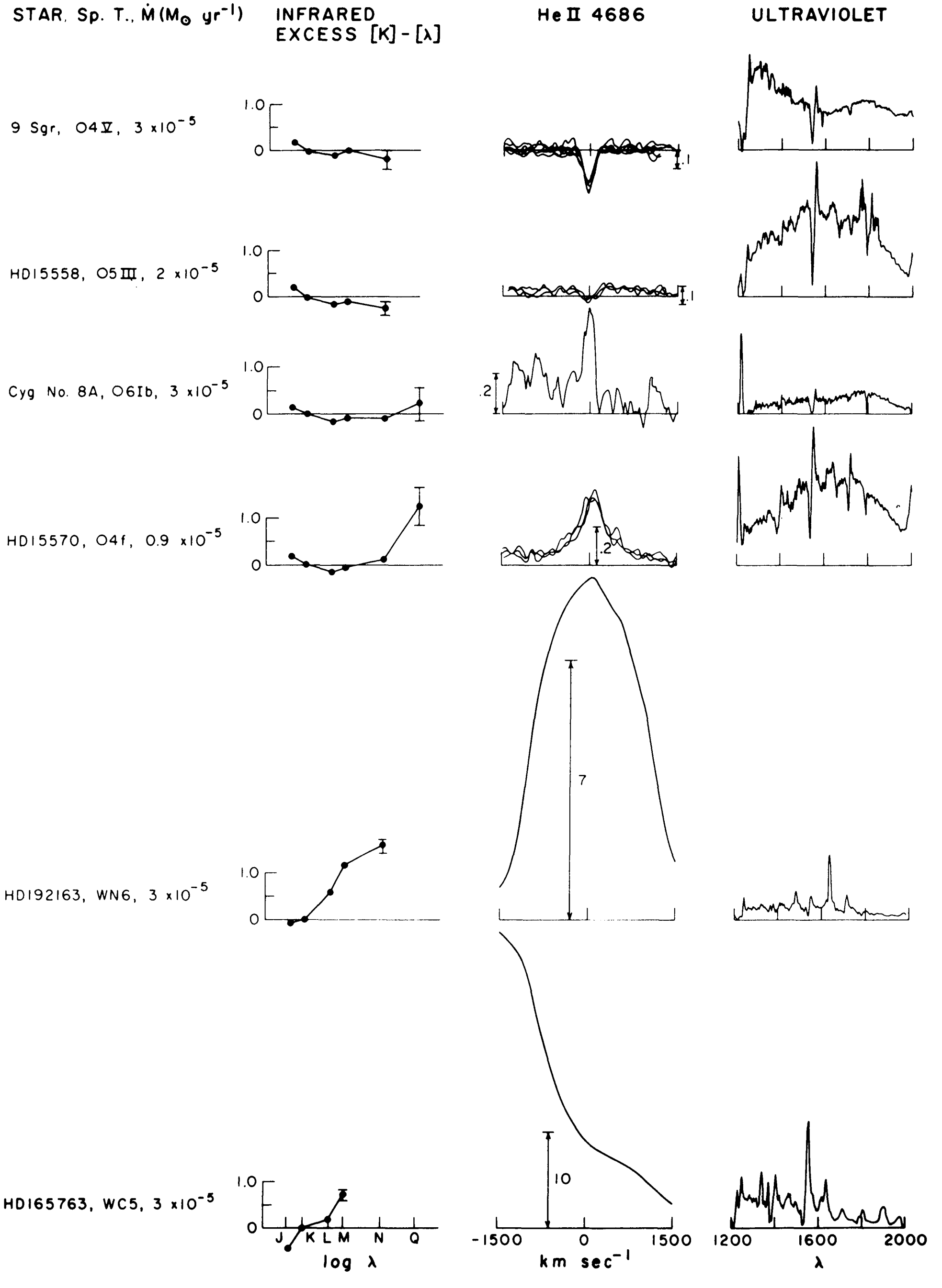

Figure 2. An evolutionary sequence of O, Of, and WR stars with constant mass loss rate.

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