THE INFLUENCE OF THE RATIO OF TOTAL TO SELECTIVE EXTINCTION ON THE DETERMINATION OF THE MASS LOSS RATE OF WOLF RAYET STARS FROM INFRARED EXCESS MEASUREMENTS

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ABSTRACT

It is shown that the mass loss rate of the WN7 star HD 93162 decreases with larger values of the ratio of total to selective extinction R. For HD 93162 the mass loss rate will change one order of magnitude, only if $\Delta R \sim 2$. Mass loss rates are derived for nine other WR stars of which visual, red and near-infrared photometric observations were obtained.

THE EXTINCTION PROBLEM

The mass loss rate ($\dot{M}$) of a Wolf Rayet star can, in principle, be determined by means of the formula

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

derived by Wright and Barlow (1975). In this formula v_∞ is the terminal velocity of the stellar wind, ν is the frequency in Hz, D is the distance of the star in kpc, Z is the r.m.s. ionic charge, μ is the mean molecular weight per ion and γ is the mean number of electrons per ion. The Gaunt factor g is calculated in the usual way (Spitzer, 1962). S_ν (in Jy) is the excess emission measured above a theoretical spectral energy distribution (e.g. a Kurucz model) at the frequence ν. In practice, before the value of S_ν is read off from the observed spectral energy distribution, this distribution is corrected for foreground interstellar extinction. Usually it is assumed that the extinction law is normal, characterized by a ratio of total to selective extinction $R = 3.1$.

In Figure 1 (thick line) the observed uncorrected spectral energy distribution of the WN7 star HD 93162 is depicted. This star is a member of the open cluster Tr 16, which is embedded in the dusty gaseous emission nebulosity in Carina. Already in 1953 Hoffleit studied

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the colour indices of O and B type stars the Carina Nebula, and found that most of these stars are highly reddened. Several investigators found subsequently that the extinction law in the Carina Nebula is anomalous. The early determinations of the ratio (R) of total to selective extinction have been discussed by Herbst (1976). Most of these R values are ∿ 5. Herbst himself using the variable extinction method found R = 4.7. Thé *et al.* 1980a) employng the colour difference method found R = 3.9, in good agreement with the results of Forte (1978). Turner and Moffat (1980) however found a normal value of R = 3.2. The differences in the result of Turner and Moffat with those of other authors is caused by the assumptions made about the observed spectral energy distribution of the used stars. Most of the O type stars in the Carina nebula exhibit excess radiation in the infrared. This can be interpreted as due to free-free emission, in which one then assumes a normal extinction law. If the infrared excess radiation is interpreted as a deficiency of the visual flux, one obtains as result an anomalous extinction law characterized by R > 3.1; the free-free emission is then assumed to be zero.

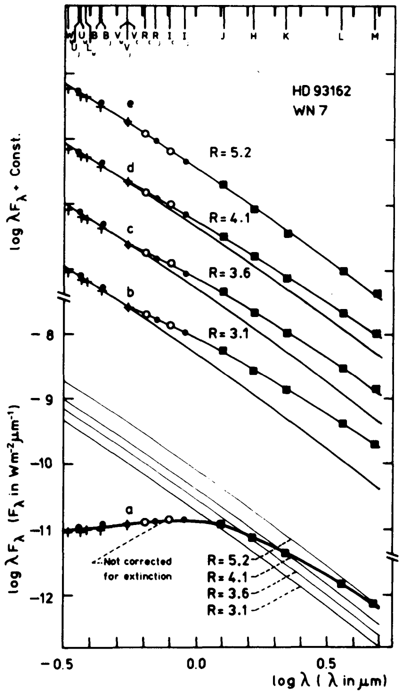

Figure 1. Observed and dereddened energy distributions for the WN7 star HD 93162.

In practice perhaps both free-free emission as well as anomalous extinction may play a role in the observed spectral energy distribution of O-type stars. We will discuss this matter further. In Figure 1 the observed energy distribution of HD 93162 is corrected for extinction with the R values 3.1, 3.6, 4.1 and 5.2, respectively. The value of E(B-V) = 0.75. At each of these figures the theoretical Kurucz (40 000 K, log g = 3.2) model is normalized at the flux through the V pass band. It is clear that the excess fluxes above the theoretical model become smaller as the R value is larger, and will disappear at R = 5.2. In Figure 1 the thin lines indicate where we actually have placed the Kurucz model, with respect to the uncorrected spectral energy distribution, in the above mentioned normalizing procedures. It is clear from this figure that we will have an excess of infrared radiation if R is assumed to be smaller than 5.2. It should be mentioned that the extinction law for R = 3.1 is van de Hulst curve No. 15, for R = 3.6 it is the curve derived from observations of the star HD 93130 (see Thé *et al.*, 1980a), for R = 4.1 that of the star Tr 16 - 100 (Thé *et al.*, 1980a), and for R = 5.2 it is the curve obtained from the observations of the star HD 93162 itself. (The method used in determining the R values is the so-called colour difference method explained by The *et al.*, 1980a).

Since the free-free emission becomes smaller when the R value is larger, it is of interest to determine how the mass loss rate changes as function of the R value. In particular we would like to know what value of ΔR will cause a change $\Delta\dot{M}$ of one order of magnitude. From the formula for the mass loss rate we write the ratios

$$\dot{M}_R : \dot{M}_{3.1} = (S_\lambda^{3/4} D^{3/2})_R : (S_\lambda^{3/4} D^{3/2})_{3.1}$$

where S_λ is the free-free flux measured above the Kurucz model at the wavelength λ. It should be noted that $\dot{M}_{5.2} = 0$ because $(S_\lambda)_{5.2} = 0$. The star HD 93162 is a member of the open cluster Tr 16 located at a distance $D_{3.1} = 2.7$ kpc if $R = 3.1$ (Thé *et al.* 1980b). The ratio of the distances for different R values can be calculated from the formula

$$\log (D_{3.1}/D_R) = 0.2\ E(B-V)\ (R-3.1),$$

where $E(B-V) = 0.75$. Using the flux at the K pass band ($\lambda = 2.2$ μm) we find the ratios

$$\dot{M}_{4.1} : \dot{M}_{3.6} : \dot{M}_{3.1} = 2.90 : 4.35 : 6.75$$

These ratios are plotted in units of $\dot{M}_{3.1}$ as function of R in Figure 2. The curve shows how the mass loss rate of HD 93162 decreases with larger values of R. A decrease of one order of magnitude in the mass loss rate is reached at $R \approx 4.9$, which means that $\Delta R \approx 1.8$. Thus in the case of HD 93162 if one assumes for R a value somewhat larger than 3.1, it will not influence the determination of the mass loss rate very much.

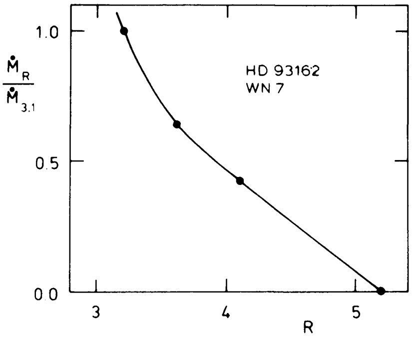

Figure 2. The mass loss rate of HD 93162 as a function of the R value.

THE MASS LOSS RATES

The spectral energy distributions of several WR stars, for which published and new data are available, are depicted in Figure 3. These distributions were obtained by correcting the original data for foreground interstellar extinction in which it is assumed that the interstellar material is obeying a normal extinction law $R = 3.1$. The colour excesses in Johnson's photometric system were determined using the narrow band photometric data and intrinsic colours as listed in van der Hucht *et al.* (1981), and the relation

$$E(B-V) = 1.23\ E(b-v) \quad .$$

Looking at Figure 3 we can make the following remarks. The star HD 62910 has a large excess infrared radiation, which perhaps is caused by the fact that this is a binary, both loosing mass. The star HD 79573 of spectral type WC6 seems to show excess IR radiation which perhaps is caused both by free emission and thermal dust re-emission. It can of course also be caused by very strong emission lines at the K and L pass bands. The star HD 92809 seems to have the same property. However, because of the lack of the L measurement we cannot draw any definitive conclusion about this matter.

The mass loss rates of the WR stars in Figure 3 are listed in Table 1. They are determined from the infrared excesses at the K or L frequencies, in a way analog to that used by Barlow *et al.* (1981). In order to predict S_ν at 5 GHz we used the spectral indices (K - 5 GHz) = 0.74 and (L - 5 GHz) = 0.71, as derived from infrared and radio measurements of HD 192163 (Hackwell *et al.*, 1974; Dickel *et al.*, 1980). Distances given in Table 1 are quoted from Hidayat *et al.* (1981). Edge velocities used are taken from Willis (1981).

For the three WN7 stars we find

$$\overline{\dot{M}}_{WN7} = 4.5 \times 10^{-5}\ M_\odot\ yr^{-1}$$

i.e a factor 1.2 larger than the average value for WN7 stars given by Barlow *et al.* (1981). The latter did not include single WC6 stars in their work. For the three WC6 stars we find

$$\overline{\dot{M}}_{WC6} = 7.3 \times 10^{-5}\ M_\odot\ yr^{-1}$$

i.e. a factor 1.8 larger than the average value for WC stars found by Barlow *et al.* (1981).

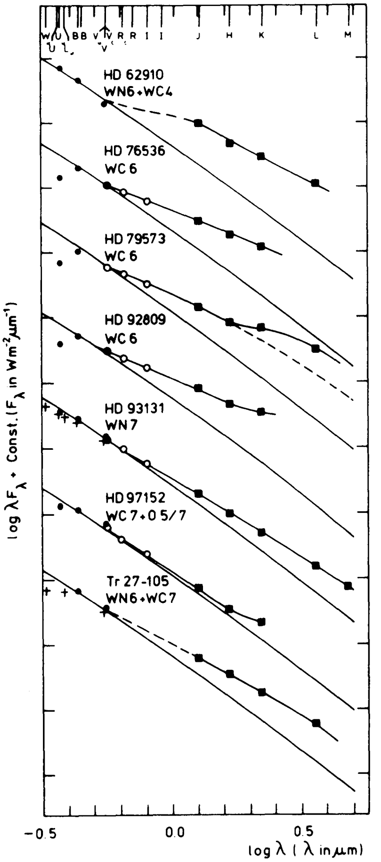

Figure 3. Dereddened energy distributions (R = 3.1) for the WR stars.

Table 1. INFRARED EXCESSES AND MASS LOSS RATES

WR	HD	Sp. Type	E_{B-V}	d(kpc)	Excess λ	Excess (Jy)	Predicted S_ν (Jy) at 5 GHz	$\dot{M}$ ($M_\odot$ yr^{-1})
8	62910	WN6 + WC4	0.82	3.47	L	0.29	2.95×10^{-4}	3.3×10^{-5}
24	93131	WN7	0.28	2.63	L	1.15	1.15×10^{-3}	6.5×10^{-5}
87	LSS 4065	WN7	1.87	2.9	L	0.53	5.3×10^{-4}	3.8×10^{-5}
89	LSS 4064	WN7	1.87	2.9	L	0.40	4.0×10^{-4}	3.1×10^{-5}
98	E 318016	WN7 + WC7	1.64	5.64	L	0.59	5.94×10^{-4}	1.2×10^{-4}
14	76536	WC6	0.46	3.47	K	1.48	7.73×10^{-4}	7.6×10^{-5}
15	79573	WC6	1.19	3.24	L	0.61	6.15×10^{-4}	5.8×10^{-5}
23	92809	WC6	0.32	4.88	K	0.87	4.55×10^{-4}	8.5×10^{-5}
42	97152	WC7 + O5-7	0.33	7.06	K	0.26	1.37×10^{-4}	6.1×10^{-5}

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