MASS LOSS RATES OF OB STARS DERIVED FROM INFRARED OBSERVATIONS

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1. INTRODUCTION

In this paper we report briefly on a study of the mass loss of early type stars in the infrared. Up to now near infrared (1.25 - 4.8 μ) broad band photometry of 70 southern OB stars of various luminosity class has been secured. Program stars have been selected, among those bright enough in the infrared to give a suitable photometric accuracy, in order to cover a wide range of spectral types (Fig. 1).

37 stars are found to exhibit emission in excess over a blackbody photospheric continuum, which is interpreted in terms of gas ejected in the form of an accelerated wind. By means of model calculations the corresponding mass loss rates are derived. The obtained values compare well with those determined indipendently by various Authors for stars in common. Our data show that mass loss rates increase with luminosity and are a decreasing function of surface gravity.

2. THE OBSERVATIONS

The observations were performed during three campaigns on February and June, 1979, and February, 1980, at the European Southern Observatory, La Silla, Chile. The infrared photometer (Kreysa, 1980 , equipped with an InSb detector and standard filters J (λ_{eff} = 1.25 μ), H (λ_{eff} = = 1.65 μ), K (λ_{eff} = 2.2 μ), L (λ_{eff} = 3.6 μ) and M (λ_{eff} = 4.8 μ), was attached to the 1 m photometric telescope.

Measurements of program stars were reduced to magnitudes in the ESO infrared photometric system (Wamsteker, 1980) by means of repeated observations of several reference stars. Reduction to unit air-mass was obtained by means of mean extinction coefficients (Wamsteker, private communication).

Correction for interstellar reddening was made with the reddening law given by Schultz et al.(1975) for filters J and K and by Sneden et al.(1978) for filter L and M (reddening in filter H has been obtained by interpolation).

3. DETERMINATION OF THE RATE OF MASS LOSS

The dereddened infrared energy distribution of each star was fitted by a two component spectrum: a blackbody to represent the stellar

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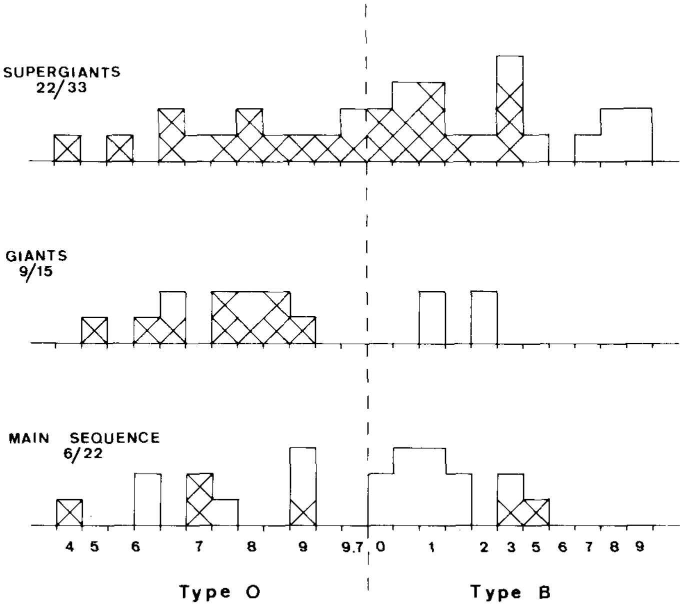

Fig. 1. Distribution of spectral types of program stars. For each luminosity class the ratio of the number of stars with substantial infrared excess (crosses) to the total, is given.

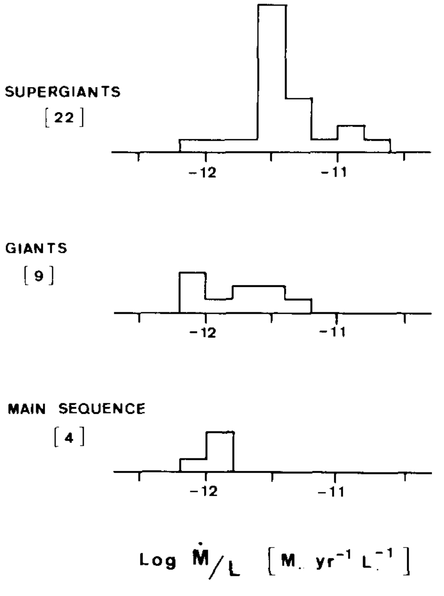

Fig. 2. Distribution of the ratio of the mass loss rate to luminosity. For each luminosity class the number of stars is given in brackets.

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photospheric continuum and a superimposed free-free and free-bound component to represent the excess emission contributed by the stellar wind.

A grid of values was assumed for the temperature of the blackbody continuum:

$$T_{IR} = \eta \, T_{eff} \quad \text{with} \quad \eta = 1.0,\ 0.85,\ 0.70 \ .$$

The contribution of the stellar wind was calculated assuming mass continuity:

$$\dot{M} = 4 \pi r^2 \rho v$$

and an acceleration law of the form:

$$v = v_o \ (r / r_o)^{\gamma} \ .$$

The initial velocity was assumed to be the sound speed unless there were indications of higher velocities at the photospheric level (Conti et al. 1977). In our grid γ takes integers from 1 to 4. The gas is assumed isothermal with $T_{gas} = T_{IR}$ and its emissivity includes free-free and free-bound processes with the assumed LTE conditions.

With the above assumptions the mass loss rate was determined for the 37 stars which have been found to exhibit significant emission in excess over the assumed blackbody continuum. The uncertainty of the derived rates arising from different choices of the parameters η and γ is typically of a factor of two. We note, however, that for marginal excesses the derived mass loss rate is critically dependent from the value of η. For fixed values of η and γ, the uncertainty of the mass loss rate depends on the accuracy of the photometry and the goodness of the fit and is typically of the order of 30%.

Mass loss rates determined taking $\eta = 0.85$ and $\gamma = 2$ compare favorably with those obtained indipendently by various Authors for stars in common. In particular, our determinations are about 30% lower than those obtained from VLA radio data (Abbot et al.,1980; 3 stars in common). The little difference is well within the experimental uncertainties, confirming thus the quality of our results. For 9 Sgr, however, the mass loss rate deduced by Abbot et al.(1980) is about 20 times higher than our determination. Since values similar to ours are also found from UV data (Gathier et al.,1980; Conti and Garmany,1980), we feel that this discrepancy is to be imputed either to problems in the radio measurements or to peculiarities of the mass flow in this star, rather than to inaccuracies of the infrared data.

Our rates agree very well with those obtained from indipendent IR observations at longer wavelengths by Barlow and Cohen (1977), their values being ~20% higher than ours for the 7 stars in common.

The mass loss rates estimated by Gathier et al.(1980) from an analysis of the ultraviolet line spectra are on the average a factor of 1.9 higher than ours for the 10 stars in common. This large difference is mostly due to their calibration of mass loss rates which is crucially based on the assumption that $\dot{M}(\zeta$ Puppis$) = 7 \times 10^{-6}\ M_{\odot} yr^{-1}$. By using a lower value of $\dot{M}(\zeta$ Pup$)$ as indicated by recent VLA results (Abbot et al. 1980) the estimates of Gathier et al.(1980) agree very well (i.e. within 30%) with ours.

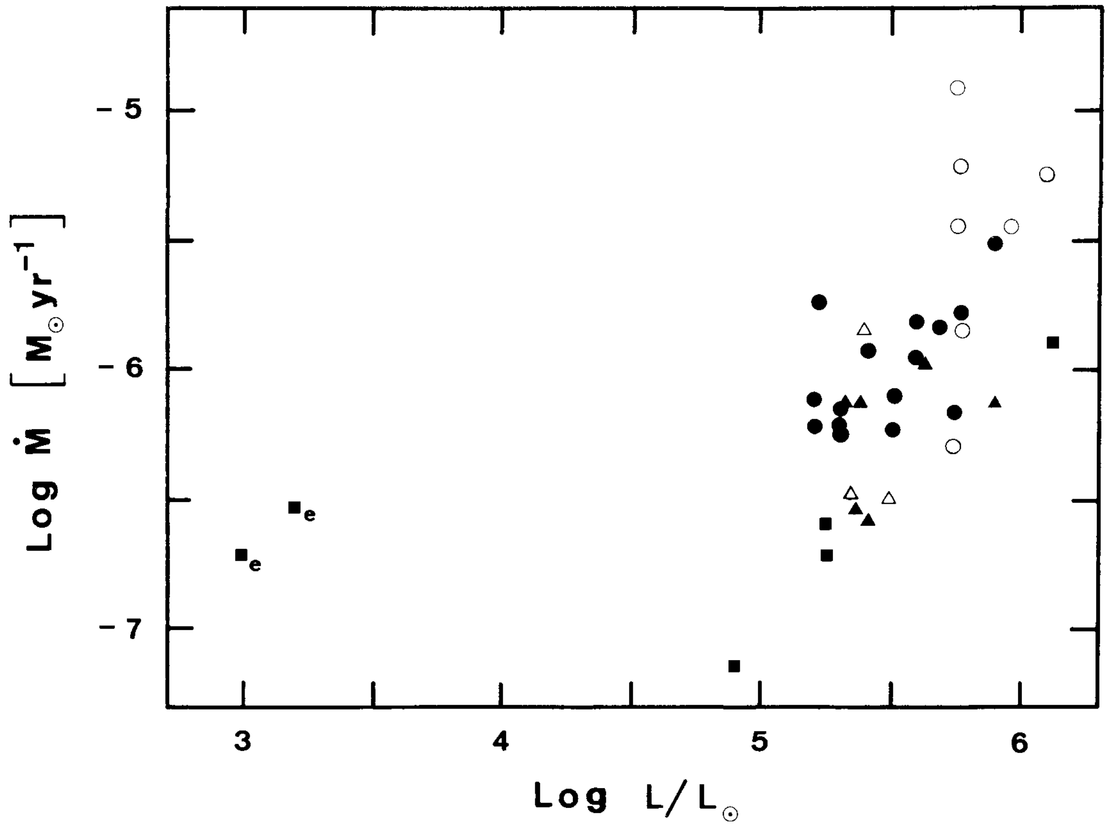

Fig. 3. Mass loss rates vs. luminosity of program stars. Circles are for supergiants, triangles for giants and squares for main sequence stars. Open symbols represent Of stars. "e" indicates Be stars.

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4. DISCUSSION

The mass loss rates derived from our IR data are shown in Fig. 3 as a function of the luminosity. An inspection of this figure reveals that a general trend can be recognized for the mass loss rate to be higher for higher luminosity. On the other hand, the large scatter prevents one from determining directly any quantitative behaviour. The scatter is drastically reduced if one considers separately stars of different luminosity class (cf. Fig. 3). For all classes, upper limits, which are omitted from Fig. 3, are fully consistent with positive detections. However, even among objects of the same luminosity class and with comparable luminosity, the mass loss rates may differ considerably from one another. Since the experimental uncertainties are not so large, this result suggests that the efficiency of the mass loss process can be related to stellar parameters in a statistical sense only.

From Fig. 3 it is apparent that Of stars do not have mass loss rates higher than those of stars with the same spectral type and luminosity class. It is possible that the Of characteristic is related to some stellar parameter (rotation ?, UV continuum ?) which does not affect directly the mass loss.

Despite the scatter, it is clear that, for equal luminosity, the mass loss rate is higher for supergiants, intermediate for giants and lower for main sequence stars. This result is better shown in Fig. 2 where the distribution of log $\dot{M}/L$ is plotted separately for the three luminosity classes. (Note that the two main sequence Be stars at the lower left corner of Fig. 3, have been omitted because part of the IR excess may not be due to mass loss). The shape of the three distributions is very similar within the statistical uncertainty, with a half width of about 0.3 . On the other hand, the mean values vary systematically being:

$< \log \dot{M}/L > = -11.41 \pm 0.07$ for supergiants (22 stars)
$< \log \dot{M}/L > = -11.74 \pm 0.09$ for giants (9 stars)
$< \log \dot{M}/L > = -11.97 \pm 0.06$ for main sequence stars (4 stars)

(units of $\dot{M}/L$ are $M_\odot\ yr^{-1} L_\odot^{-1}$). The differences between these average values are statistically significant and suggest a smooth transition from supergiants through giants to main sequence stars. This result indicates that in addition to luminosity another continously varying parameter (possibly gravity) contributes to determine the mass loss rate of a star.

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DISCUSSION

DE LOORE: I do not agree with your conclusion about the mass loss rates of Of-stars. In the picture I want to show here (I will show it again in my talk of Friday) you can see for yourself than the mass-loss rates of Of-star are systematically higher. In the figure are indicated the mass loss rates I could pick up from the literature (UV - IR) and your mass loss rates are included by squares: open for O stars, filled squares for Of stars - circles (open for O, filled for Of) come from other authors. You will remark that all the Of's are in the upper half of the figure. I agree that there is a large spread in the $\dot{M}$ for the Of of the same spectral type, however, this spread is also present for the other O-stars. So I do not agree with your statement that not necessarily the Of stars should lose more mass than the normal O-stars.

PANAGIA: In our sample the Of stars do not exhibit any larger mass loss rate than "normal" O-type stars with equal spectral type and luminosity class. In particular, for main sequence stars with not Of characteristic we find log $\dot{M}/L = -11.97 \pm 0.27$ and for the one class V Of star (HD 171589) log $\dot{M}/L = -11.81$. Similarly, for giants log $\dot{M}/L$ (normal O-type) = -11.72 ± 0.31 and log $\dot{M}/L$ (Of) = -11.74 ± 0.35. For supergiants log $\dot{M}/L$ (normal O type) = -11.41 ± 0.28 and log $\dot{M}/L$ (Of) = -11.42 ± 0.61. These results do not indicate any systematic difference of mass loss rate between Of's and not- Of's. The apparent higher mass loss rate of a number of Of stars relative to other O-type stars is due to the fact that most Of stars are also supergiants. These, indeed, have the intrinsically higher mass loss rate than all other O-type stars, namely giants and supergiants.

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