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Pulsation and instability amongst the most luminous stars

ABSTRACT

The red supergiant variables in the LMC show well defined period–luminosity and period–mass loss relations. It is probably that these stars, with typical initial masses of ~20 $M_\odot$, are pulsating in the first overtone and have low effective temperatures (~2800K). The blue progenitor of SN1987A had a similar luminosity to the red supergiant variables and will thus have evolved through such a stage. The non–spherical mass loss giving rise to the ring round SN1987A probably occurred in the blue supergiant phase. Whether this ring also involves matter ejected in the red supergiant stage is not entirely clear since the luminous blue variable AG Car with a ring of comparable size is now believed to be too luminous ever to have been a red supergiant.

INTRODUCTION

It has been known for more than 30 years that there is an upper limit at M_{bol} ~ –11 to the luminosities of the hotter super– (or hyper–) giants in the Magellanic Clouds, and that at (and slightly below) this limit, the stars show emission lines indicative of instability and mass loss (Feast, Thackeray and Wesselink 1960). These results strongly suggested that the upper luminosity limit is set by physical processes which we see currently at work in the most luminous stars rather than being determined by constraints at an early stage of star formation (e.g. limitations in the initial mass function). The detailed study of the instabilities in these hotter stars has been very fruitful. Studies of the cool supergiants, which extend up to luminosities of M_{bol} ~ –9.5 in the LMC, and of post red–supergiant stars, have been less extensive and this paper concentrates on these latter aspects of the supergiant problem.

RED SUPERGIANT VARIABLES

Some years ago it was noticed by Wood *et al.* (1983) using a combination of Mt Stromlo, AAO and SAAO infrared photometry (JHK) that in an M_{bol}– or M_K–period plot for cool variables in the Magellanic Clouds, there was a rather clear separation between supergiants and lower luminosity variables which are presumably AGB stars.

The most important AGB variables are the Miras. These stars are not directly relevant to the present discussion being low mass objects. However it is worth recalling that work in recent years has shown that these objects are a rather "well–behaved" group, conforming to a number of regularities. They give well defined PL and PLC relations. In addition, mass loss (as measured for instance by IRAS colours) is strongly correlated with period and light amplitude, making them the best example (perhaps the only good example) of a strong connection between mass loss and pulsation (cf. Feast *et al.* 1989, Whitelock *et al.* 1987, Whitelock *et al.* 1991). These results encourage one to look for similar regularities amongst the red supergiant variables which have about the same surface temperatures (judging by their (J–K) colours) and similar, low, surface gravities.

The best place to study the red supergiant variables is the LMC, primarily because of the common and well determined distance modulus. A significant improvement in the discussion of Wood *et al.* (1983) can be made since we now have available IRAS data for 16 of the red supergiant variables in the LMC (cf. Reid *et al.* 1990). Except in one case the fluxes are quite small and have substantial uncertainties. They also refer only to a limited number of epochs. However the results show that there is a considerable proportion of the total flux of these stars in the far infrared. For 15 of the variables the luminosities derived from JHK and the IRAS data are on average 33% greater than those previously derived from JHK alone. The one remaining variable is highly obscured by its circumstellar dust shell which radiates about 75% of the total flux of the system (Elias *et al.* 1986). This variable is also an OH source (Wood *et al.* 1986) and has an especially long period (log P ~ 3.1) (Wood *et al.* 1991).

Figure 1 shows the P–L relation for these variables using the luminosities calculated by Reid *et al.* (1990), which include the IRAS data, adjusted to an LMC modulus of 18.55 (Feast 1991). When one considers the observational uncertainties and that full light curves have not been obtained in either JHK or the IRAS colours, the scatter in the diagram is remarkably small. For log P < 2.91 a least squares fit gives

$$M_{bol} = -2.38 \log P - 1.46 \qquad \sigma = 0^m.15.$$

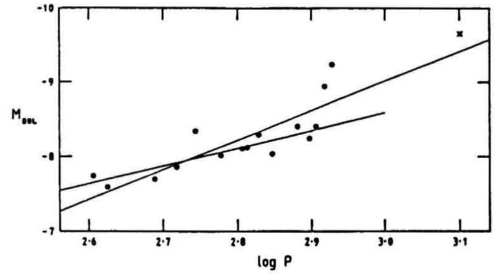

Fig. 1: The period–luminosity relation for LMC red supergiant variables with known periods as well as JHK and IRAS fluxes. The cross is an OH source. The lines are the two least squares solutions discussed in the text.

Where σ is the standard deviation.
It is possible that there is a step in the relation beyond log P ~ 2.9; that is not yet clear. A line through all 16 points gives

$M_{bol} = -3.96 \log P + 2.87 \qquad \sigma = 0^{m}.27.$

MASS LOSS OF RED SUPERGIANT VARIABLES

It is possible to make estimates of the mass loss rates for these stars using the IRAS data. Reid *et al.* (1990) do this by assuming Jura's (1987) formula

$-\dot{M} = 1.7 \times 10^{-7}\ V_{15}\ r^2\ L^{-1/2}\ S\nu(60)\ \lambda_{10}^{\frac{1}{2}}\ M_\odot\ yr^{-1}$

where

V_{15} = Outflow velocity in 15 km s^{-1} units
λ_{10} = Average wavelength of flux distribution in 10μm units
r = Distance in kpc
L = Luminosity in $10^4\ L_\odot$
$S\nu(60)$ = IRAS 60μm flux.

Reid *et al.* put $V_{15} = \lambda_{10} = 1$ and (since $S\nu(60)$ is not generally measured) $0.5\ S\nu\ (25) = S\nu(60)$.

It must be recognized that the mass loss rates derived in this way are quite uncertain due to uncertainties in the measured fluxes, the assumptions made in deriving Jura's relation and the further numerical approximations made in applying it to these stars. In view of this the low scatter in the log($-\dot{M}$), log P plot (Figure 2) is rather striking. A least squares fit shows $-\dot{M}$ increasing with P according to the relation.

$\log(-\dot{M}) = 1.32 \log P - 8.17 \qquad \sigma = 0.18$

This relation omits the OH object at log P ~ 3.1 which, as one might expect, has a much higher mass loss rate than the rest. Objects like this source (IRAS 04553–6825) must be quite rare. There is one other known LMC IRAS source of similar luminosity (IRAS 05346–6949) which has

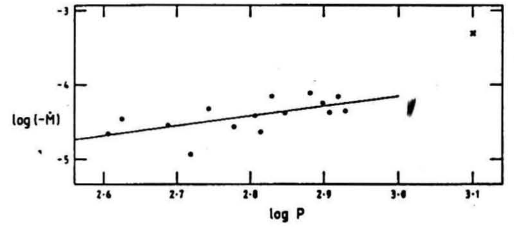

Fig. 2: The period–mass loss relation for the red supergiant variables of figure 1. The line is a least square fit to the points (except for the OH source which is marked as a cross).

M_{bol} ~ –9.4 and which has an even thicker shell than 04553–6825 (K~16 against K~7 for 04553–6825) (Elias *et al.* 1986). However it is not known whether this second source is variable and it is not in the list of LMC OH detections (Wood *et al.* 1991).

Nieuwenhuijzen and de Jager (1990) have suggested a general empirical relation for mass loss of the form

$$-\dot{M} = 9.62 \times 10^{-15}\ (L/L_\odot)^{1.24}\ (M/M_\odot)^{0.16}\ (R/R_\odot)^{0.81}\ M_\odot\ yr^{-1}$$

Since a typical luminosity for these variables is M_{bol} ~ –8, a typical initial mass is ~ 20 $M_\odot$ according to the models of Maeder and Meynet (1988). Then with either of the two temperature scales discussed below one finds $-\dot{M} \sim 1 \times 10^{-5}\ M_\odot\ yr^{-1}$. The values derived from Jura's relation (cf. Fig. 2) are comparable but about three times greater. The empirical parameterization of $-\dot{M}$ in terms of luminosity and temperature by de Jager *et al.* (1988) gives mass loss rates which are an order of magnitude smaller than those from Jura's relation.

PULSATION MASSES FOR RED SUPERGIANT VARIABLES

In order to derive a mass from a PL relation one requires a theoretical pulsation equation and an estimate of effective temperature. This latter quantity is poorly known for red supergiants. At low temperatures the relation between intrinsic colour and temperature is quite uncertain and in addition these stars may suffer significant circumstellar reddening. The mean (J–K) of the LMC supergiant variables (omitting the OH source) is 1.23 ($(J-K)_0$ = 1.19) and there is no significant dependence on period though such a dependence could be hidden by the scatter ($\sigma = 0^{m}.09$).

Two calibrations of effective temperature in terms of $(J-K)_0$ have been used by various groups in recent times. Neither is very certain, at least as far as applicability to cool supergiant variables is concerned. One of these calibrations is justified on the basis of angular diameter measurements of normal (non-variable) M giants, the other may be applicable to Mira variables (cf. Ridgway *et al.* 1980, Glass and Feast 1982, Wood *et al.* 1989, Feast *et al.* 1989). For $(J-K)_0 = 1.19$ these calibrations give T = 3415K and 2793K respectively. It is useful to see what conclusions follow from adopting each of these temperatures.

If we assume that red supergiant variables are radial pulsators then model calculations (Fox and Wood 1982) show that

$\log P_0 = -2.651 + 2.2\log(R/R_\odot) - 0.83\log(M/M_\odot)$ for fundamental pulsators and,

$\log P_1 = -1.420 + 1.5\log(R/R_\odot) - 0.5\log(M/M_\odot)$ for the first overtone.

One would like to know how the pulsation mass varies with period for these stars but this depends critically on a possible period–temperature relation which is poorly known. We thus consider typical mean values only. For the two different pulsation modes and the two different temperature calibrations one then obtains:

Option	Mode	T	Pulsation Mass ($M_\odot$)
(a)	Fundamental	2793K	85
(b)	Fundamental	3415K	30
(c)	First overtone	3415K	5
(d)	First overtone	2793K	15

These results are very approximate. However they show some interesting features. Since (as noted above) evolutionary tracks suggest initial masses of ~20 $M_\odot$ for these objects, option (a) is clearly ruled out. Given the uncertainties, option (b) is perhaps not entirely excluded but seems rather unlikely. Options (c) and (d) show that overtone pulsation with either temperature is possible. Option (c) implies heavy mass loss during evolution. Option (d) implies more moderate mass loss.

It will not be possible to decide (from observations of red supergiant variables alone) which of these two options ((c) or (d)) is nearer the truth until the temperature scale is more precisely calibrated. Amongst other things the problem is of importance for our understanding of the possible blueward evolution of stars following the red supergiant phase and in particular for our understanding of the SN1987A progenitor. The progenitor was blue and had M_{bol} ~ −7.8 (cf. Arnett *et al.* 1989). Thus for nearly horizontal evolutionary tracks it will have presumably evolved through the red supergiant variable stage. Both high and moderate mass–loss models for the evolution of the progenitor have been discussed and options (c) and (d) correspond very roughly to these two cases.

MASS LOSS AND THE PROGENITOR OF SN1987A

The high mass loss solution (c) would have removed all, or practically all, the hydrogen envelope even in the red supergiant phase. Arguments have been raised against such a progenitor for SN1987A (cf. Arnett *et al.* 1989); it being held that a substantial hydrogen envelope was present at explosion (and of course the progenitor was a B–type star not a WR star).

Woosley *et al.* (1988) have computed moderate mass loss models (three times the "de Jager" mass loss rate i.e. about the rate we derived for the red supergiant variables). These models have an initial mass of 18 $M_\odot$ and a mass at explosion of 16.2 $M_\odot$. In view of the various uncertainties this is probably not inconsistent with our option (d).

In this work one has to remember that there is a problem concerning the chemical abundances that have been adopted for evolutionary calculations in the LMC (cf. Feast 1989). The oxygen abundance is particularly important and recent builders of models for the SN1987A progenitor have used a value three times less than solar. There seems to be difficulties in obtaining a blue progenitor with higher oxygen abundances (cf. Arnett *et al.* 1989 and references there). A comparison of abundances derived from LMC HII regions with solar values does indeed suggest an oxygen deficiency of about the adopted value (e.g. Dufour 1984 gives a deficiency of a factor 2.8). However, a direct comparison of abundances in HII region in the LMC and in the solar neighbourhood should be more reliable as avoiding various sources of systematic error. This indicates an oxygen deficiency in the LMC of only a factor 1.8 (Dufour 1984). It would be important to examine in detail whether post red supergiant evolutionary tracks are possible with this latter abundance.

NON–SPHERICAL MASS LOSS FROM EVOLVED SUPERGIANTS

SN1987A raises another problem regarding the instability of massive stars. Observations show the post–supernova to be surrounded by a 1.7 arcsec diameter bright elliptical ring (e.g. Jakobsen *et al.* 1991). This ring has been widely regarded as a dense region caused by the interaction of a fast wind from the blue supergiant progenitor with a slow wind originating in the previous red supergiant phase. This region of density enhancement is now illuminated by the supernova. The evidence that this is a ring and not a spherical shell evidently requires non–spherical mass loss in either the red supergiant or blue supergiant phases (or asymmetry in the radiation from the supernova which is probably less likely).

The observations previously discussed can be used to show that non–spherical ejection is unlikely to be significant in the red supergiant phase. The dust emission from the LMC red supergiant variables is ~25% of their total flux. Thus if the dust were confined to a band covering only 25% of the star, this region would be optically thick and the apparent bolometric magnitude would vary by 1.5 mag depending on the angle of view. The small spread in the P–L relation (figure 1) shows that there cannot be a gross departure from spherical symmetry of this kind.

This implies that the mass loss in the post red–supergiant phase must be non–spherical. In fact there is evidence that some massive evolved blue stars suffer non–spherical mass loss. The best example is AG Car. The velocities (Thackeray 1977) and ellipticity of the nebulosity round this star strongly suggest a ring structure. The diameter of the AG Car ring (3 light years for a distance of 6 kpc (Humphreys *et al.* 1989)) is comparable with that of SN1987A (1.3 light years).

Whilst this result is consistent with the hypothesis that non–spherical mass loss occurs in the blue supergiant phase it is important to notice that Humphreys *et al.* believe that AG Car is too luminous to have ever evolved through a red supergiant phase. If this is so then it cannot be assumed without other evidence that the ring round SN1987A involves matter ejected in the red supergiant phase.

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REFERENCES

Arnett, W.D., Bahcall, J.N., Kirshner, R.P. and Woosley, S.E., 1989. *Ann. Rev. Ast. Astrophys.* **27**, 629.

de Jager, C., Nieuwenhuijzen, H. and van der Hucht, K.A., 1988. *A.A. Sup.* **72**, 259.

Dufour, R.J. 1984 in *Structure and Evolution of the Magellanic Clouds* (*IAU Symposium 108*) ed. S van den Bergh and K S de Boer (Reidel, Dordrecht) p 353.

Elias, J.H., Frogel, J.A. and Schwering, P.B.W., 1986. *Ap.J.* **302**, 675.

Feast, M.W., Thackeray, A.D. and Wesselink, A.J., 1960. *M.N.* **121**, 337.

Feast, M.W., 1989 in *The World of Galaxies* ed. H.G. Corwin and L. Bottinelli (Springer–Verlag) p 118.

Feast, M.W., Glass, I.S., Whitelock, P.A. and Catchpole, R.M., 1989. *M.N.* **241**, 375.

Feast, M.W., 1991 in "*Observational Tests of Inflation*" NATO Advanced Research Workshop, in press

Fox, M.W. and Wood, P.R., 1982. *Ap.J.* **259**, 198.

Glass, I.S. and Feast, M.W., 1982. *M.N.* **199**, 245.

Humphreys, R.M., Lamers, H.J.G.L.M., Hoekzema, N. and Cassatella, A., 1989. *A.A.* **218**, L17

Jakobsen, P. and others 1991. *Ap.J.*, in press.

Jura, M., 1987. *Ap.J.* **313**, 743.

Maeder, A. and Meynet, G., 1988. *A.A. Sup.* **76**, 411.

Nieuwenhuijzen, H. and de Jager, C., 1990. *A.A.* **231**, 134.

Ridgway, S.T., Joyce, R.R., White, N.M. and Wing, R.F., 1980. *Ap.J.* **235**, 126.

Reid, N., Tinney, C. and Mould, J., 1990. *Ap.J.* **348**, 98.

Thackeray, A.D., 1977. *M.N.* **180**, 95.

Whitelock, P.A., Pottasch, S.R. and Feast, M.W., 1987 in *Late Stages of Stellar Evolution* p 269, ed. Kwok S. and Pottasch, S.R., Reidel, Dordrecht.

Whitelock, P.A., Feast, M.W. and Catchpole, R.M., 1991. *M.N.* **248**, 276.

Wood, P.R., Bessell, M.S. and Whiteoak, J.B., 1986. *Ap.J.*, **306**, L81.

Wood, P.R., Bessell, M.S. and Fox, M.W., 1983. *Ap.J.* **272**, 99.

Wood, P.R., Moore, G. and Hughes, S.M.G., 1991 in *IAU Symposium 148* (Sydney).

Woosley, S.E., Pinto, P.A. and Weaver, T.A., 1988. *Proc. Ast. Soc. Aust.*, **7**, 355.

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