MASS LOSS FROM LUMINOUS BLUE VARIABLES

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1. INTRODUCTION

Luminous Blue Variables (LBV's) are losing mass at a rate which is higher than in normal stars of the same luminosity. This high mass loss is evident from the occurrence of P Cygni profiles in the visual spectrum, the large numbers of UV lines which are Doppler shifted or show P Cygni profiles and the large IR excess or radio free-free emission. Mass loss from LBV's is strongly variable on a wide range of timescales from months to centuries and possibly even millenia. During these variations the mass loss may vary from values as low as 10^{-6} to 10^{-5} $M_\odot$/yr, when the star is quiet, to outbursts of the type observed in P Cygni in AD 1600 and η Car in 1837 (for reviews see Davidson, 1987; Lamers, 1986, 1987).

The variability of mass loss is related to the photometric variability, in that $\dot{M}$ is higher when the star is visually brighter at lower T_{eff}. Since the observations of a small number of LBV's suggest that the photometric variations are due to changes in T_{eff} and R_* at constant L, we may conclude that $\dot{M}$ is highest when the photospheric radius is largest and the gravity is smallest.

The size of the variations in R_* and T_{eff} can be very substantial; e.g., the star S Dor changed from $T_{eff} \simeq 22000$ K and $R_* \simeq 44$ $R_\odot$ during minimum V = 11.3 in 1965 to $T_{eff} \simeq 8000$ K and $R_* \simeq 330$ $R_\odot$ during maximum V = 9.3 in 1983. The mass loss rate was 5×10^{-5} $M_\odot$/yr at maximum; the mass loss rate at minimum is unknown (Leitherer et al., 1985; Lamers, 1987). (It is worth noting that the values of T_{eff} and R_* are ill-defined in extended atmospheres because $R(\tau_\lambda \simeq 1)$ depends on λ. The values of T_{eff} given in this paper are some kind of spectroscopic or photometric temperature and R_* is the corresponding value derived from $L = 4\pi R_*^2 T_{eff}^4$).

What causes the variations in R_*, T_{eff}, and $\dot{M}$? This is a chicken and egg problem: 1) does R_* increase because some subphotospheric

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mechanism forces the star to a higher mass loss rate so that $R(\tau \simeq 1)$ moves outward or 2) does $\dot{M}$ increase because some subphotospheric mechanism increases R_* and decreases g? The study of R71 by Leitherer et al. (1989) suggests that 2) is the more likely possibility. This replaces the question about the origin of the variable $\dot{M}$ by the question about the mechanism for the variations in R_*.

We should emphasize that the situation regarding the large eruptions is not clear at all. The fact that as much as ~1 $M_\odot$ can be ejected in a major eruption suggests an instability located deep below the photosphere (Davidson, 1989).

In this paper I will discuss the observational evidence for mass loss from LBV's and its variability. I will try to derive "time-averaged" mass loss rates which are important because of their evolutionary consequences. I must apologize that the values which I will derive are rather uncertain for the simple reason that the number of LBV's for which mass loss has been estimated is very small. The estimates about the variability of mass loss are even more scarce and the information about large eruptions is limited to two or three stars only. So the "time-averaged mass loss rates" depend on low number statistics. Unfortunately we cannot do better at the moment.

2. VARIABILITY AND TERMINOLOGY

A typical LBV light curve is shown in Fig. 1 for AG Car between 1969 and 1985 (Viotti, 1988). The maximum amplitude is $\Delta V = 2\overset{m}{.}6$, but the typical "ups and downs" have a range of $0\overset{m}{.}5 \lesssim \Delta V \lesssim 2\overset{m}{.}0$. I will call these the moderate variations. They are the characteristic LBV variations for which the mechanism is unknown. They seem to occur at constant L, and so ΔV is due to variations in the Bolometric Correction. The variations are not periodic but occur on a peak-to-peak timescale of years (in AG Car) to two decades (in S Dor). The maxima should not be called "outbursts," although this name is often used in the literature, because the observations show that they are extended periods of high mass loss which last considerably longer than the expected dynamical timescales for real outbursts. I will refer to "maxima" and "minima."

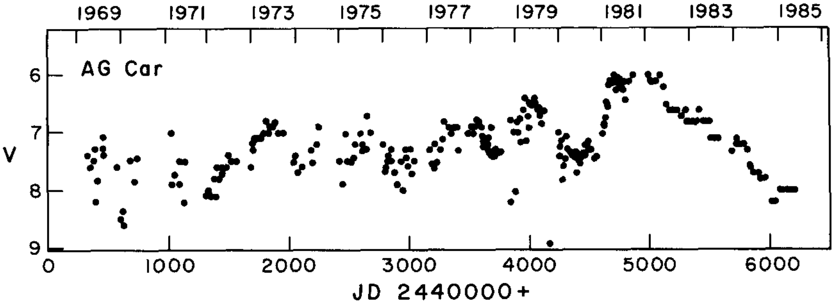

Fig. 1. The light curve of AG Car as an example of a typical LBV light curve (Viotti, 1988).

In addition to the moderate variations, the LBV's which have been studied in detail show photometric micro-variations of $\Delta V \lesssim 0^{m}\!.2$ on timescales of months to weeks (Van Genderen, 1986; Lamers, 1987). They are probably due to non-radial pulsations.

Some LBV's, such as P Cyg, η Car and V12 in NGC 2403 have shown major brightening of $\Delta V \gtrsim 3^{m}$ connected with large mass ejection in the recorded history. I will call these eruptions, although their real nature is not known. Other LBV's, such as AG Car and R127 are surrounded by rings or shells which indicate that large amounts of mass were ejected in the past.

Some LBV's, such as P Cyg and possibly η Car, go through extended periods of quiescence, which may last for a century, in which the moderate variations are absent or diminished to $\Delta V \lesssim 0^{m}\!.3$. It is possible that the quiescence is due to the occurrence of eruptions previously. It is not known whether quiescence should be considered as an extended minimum or an extended maximum.

I will discuss the mass loss rates at the various phases separately. In reality there is probably a continuous transition between minima and maxima and quiescence.

3. PRESENT MASS LOSS RATES OF LBV'S

3.1. Mass Loss During Quiescence or at Minimum

The mass loss rate during quiescence or at minimum has been determined for a few LBV's only (Table 1).

P Cygni: The most accurate estimate of $\dot{M}$ is based on the free-free radio emission (Abbott et al., 1981; White and Becker, 1982). This $\dot{M}$ depends only on the distance and the parameters of the star, for which we adopted the values of Lamers et al. (1983).

η Car: Van Genderen and Thé (1985) and Davidson et al. (1986) derived upper limits for the present mass loss rate of $\dot{M} \lesssim 10^{-3}$ $M_{\odot}$/yr. Davidson et al. argued that the temperature of the pseudo-photosphere would be less than the observed value of $T \simeq 30000$ K if $\dot{M}$ was larger than this value. The much higher rate of 10^{-2} - 10^{-1} $M_{\odot}$/yr derived from the amount of dust in the homunculus (Andriesse et al., 1978; Hyland et al., 1979) does not represent the present $\dot{M}$, but some average over the last centuries.

R71: The parameters of this star at minimum in 1980 and its mass loss rate of $\dot{M} = -6 \times 10^{-7}$ $M_{\odot}$/yr have been determined by Leitherer et al. (1989) from a study of the H and He lines and the energy distribution, using non-LTE model atmospheres and self-consistent wind models.

3.2. Mass Loss During Maximum

AG Car: We adopt the stellar parameters and the new distance determination of 7.1 kpc derived from the radial velocity and from the studies of normal stars close to AG Car (Humphreys et al., 1989; Lamers et al., 1989). The mass loss rate is highly variable: during the maximum of 1981 (V=6.1) the visual spectrum showed many strong P Cygni profiles, whereas during minimum in 1975 (V=7.4) it showed

Table 1. Mass loss rates of LBV's

Galaxy	Star	Phase	Type	V	log d (pc)	M_{bol}	T_{eff}	R_* ($R_\odot$)	v_∞ (km/s)	Ref	log $\dot{M}$ ($M_\odot$/yr)	Method	Ref	$\frac{\dot{M} v_\infty}{L/c}$
MW	P Cyg	Quies	B1 Ia$^+$	4.8	3.26	- 9.9	19300	76	210	1,2	-5.0	Radio	3,4	0.14
	η Car	Quies	--	6.0	3.40	-11.8	30000	76	700	5	<-3.0	Phot.	5,6	<8
	AG Car	Max	B5 Ia	6.1	3.85	-11.3	13700	290	166	7,8	-4.6	HI	9	0.08
LMC	R71	Min	B2.5 Iep	10.9	4.66	-8.8	16000	88	170	10	-6.2	HI, IR	10	0.02
		Max	A1 I	9.9	4.66		10000	330	110	10	-4.7	HI, IR	10	0.41
	S Dor	Max	Aeq	9.5	4.66	-9.5	10000	430	110	10,11	-4.5	HI, IR	10	0.34
	R127	Max	B5 I	10.4	4.66	-10.6	17000	140	200	12	-4.2:	HI, IR	12	0.45:
M31	Var A1	?	--	16.6	5.82	-10.3	15000	150	150	13,14	-5.1	HI	14	0.06
	Var 15	Max	--	17.3	5.82	-9.2	9000	250	200	13,14	-4.3	HI	14	1.30
	AF And	Min:	--	16.4	5.82	-10.0	28000	38	300	13,14	-4.8	HI	14	0.30
M33	Var B	Min:	--	16.2	5.78	-10.5	25000	60	150	13,14	-5.2	HI	14	0.04
	Var C	Max:	--	17.2	5.78	-9.8	7800	440	175	13,14	-4.4	HI	14	0.52
	Var 83	Min:	--	16.2	5.78	-10.8	20000	110	120	13,14	-5.1	HI	14	0.03

References

1. Lamers et al., 1983
2. Lamers et al., 1985
3. Abbott et al., 1981
4. White and Becker, 1982
5. Davidson et al., 1986
6. van Genderen and Thé, 1985
7. Humphreys et al., 1989
8. Lamers et al., 1989
9. Wolf and Stahl, 1982
10. Leitherer et al., 1989
11. Leitherer et al., 1985
12. Stahl et al., 1983
13. Humphreys et al. 1984
14. Humphreys, 1989

emission lines of H I, He I and [Fe II] (Wolf and Stahl, 1982; Whitelock et al., 1983). The mass loss rate has been derived for the maximum only from the extended Balmer emission wings, which are attributed to electron scattering by Wolf and Stahl (1982) who found $\dot{M} \approx 3 \times 10^{-5}$ $M_\odot$/yr. These authors assumed $R = 130$ $R_\odot$. Correcting for the larger radius of 290 $R_\odot$ adopted here, we find $\dot{M} \approx 7 \times 10^{-5}$ $M_\odot$/yr. This may be an overestimate since part of the emission wings may be due to non-LTE effects (Hubeny and Leitherer, 1989). On the other hand, the spectra of AG Car at the 1981-maximum is very similar to that of S Dor during its 1986-maximum (Wolf and Stahl, 1982) for which Leitherer et al. (1989) derived 3×10^{-5} $M_\odot$/yr. We conclude that the mass loss rate of AG Car during maximum is $\dot{M} \approx 2 - 7 \times 10^{-5}$ $M_\odot$/yr.

R71 and S Dor: Leitherer et al. (1989) derived the mass loss rate during the 1983-maximum of S Dor at V = 9.5 and during the 1974-maximum of R71 at V = 9.9 from the H I profiles and from the energy distributions using non-LTE models and self-consistent wind calculations. They found $\dot{M} = 2 \times 10^{-5}$ $M_\odot$/yr for both stars, if they assume that both stars have $L = 3 \times 10^5$ $L_\odot$. In reality the luminosities are $L = 5 \times 10^5$ $L_\odot$ for S Dor and $L \approx 3 \times 10^5$ for R71 if a distance modulus of 18.3 and E(B-V) = 0.15 is adopted. Consequently we adopt 3×10^{-5} $M_\odot$/yr for S Dor after correction for the larger radius of this star.

R127: The variability of this star has been described by Walborn (1977, 1982), Stahl et al. (1983), and Stahl and Wolf (1986). The mass loss rate of 6×10^{-5} $M_\odot$/yr during the 1982-maximum (V=10.4) was estimated by Stahl et al. (1983) from the strength of the Balmer emission and from the IR excess. They adopted a ballistic velocity law, which is certainly wrong. So this mass loss rate is uncertain by about a factor of 3.

3.3. Mass Loss From LBV's in M31 and M33

Humphreys et al. (1984), Kenyon and Gallagher (1985), and Humphreys (1989) have studied the LBV's in M31 and M33. The mass loss rates were derived from the Balmer profiles and from the IR excess. The stellar parameters and the mass loss rates are listed in Table 1. For most of these stars, we do not known whether the derived rates represent those at minimum, at maximum, or inbetween, except for Var 15 in M31 which was observed at maximum. Judging from the temperatures we would suspect that Var C in M33 was at maximum because $T \approx 7500 - 8000$ K, and that AF And, Var B and Var 83 in M33 with $T \gtrsim 20000$ K were probably close to minimum. The phase of Var A1 in M31 is unknown.

3.4. Conclusions

The mass loss rates of the LBV's are plotted versus M_{bol} in Fig. 2. The mean relation for O-stars (Garmany and Conti, 1984) is shown for comparison. We can draw the following conclusions.

1. The mass loss rates at maximum are about the same for all LBV's: $\log \dot{M} = -4.43 \pm 0.15$. The maxima used here are not absolute maxima, so the differences in the range of $-4.6 \leq \log \dot{M}_{max} \leq -4.3$ are probably real.

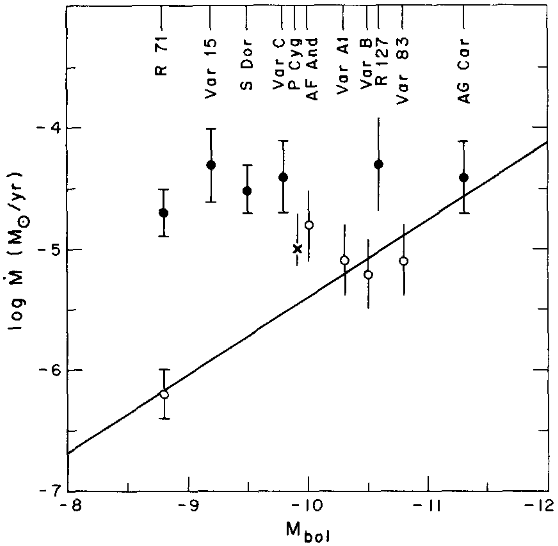

Fig. 2. Mass loss versus M_{bol} for LBV's at different phases: filled circles = maximum; open circles = minimum; cross = quiescence. The line is the $\dot{M}$ - M_{bol} relation for normal stars. The mass loss of LBV's at maximum is about constant at $\dot{M} \simeq 3 \times 10^{-5}$ $M_\odot$/yr. The mass loss at minimum is similar to that of normal stars.

2. The mass loss rates at minimum seem to follow the relation for normal stars. The only exception is AF And in M31. The star P Cygni during quiescence has a 3 times higher mass loss than the mean $\dot{M}$-L relation for normal stars. This does not necessarily imply that $\dot{M}$ is higher than predicted by the radiation driven wind theory. Pauldrach et al. (1986) have shown that the mass loss of P Cygni in quiescence agrees with the predictions, because P Cyg has a lower mass than normal stars of the same luminosity. Unfortunately we do not know the parameters of the LBV's accurately enough to make this comparison between predicted and observed $\dot{M}$ for each star. However, the fact that the observable and predicted rates agree for the two LBV's with reasonably well determined parameters, i.e. P Cyg and R71 at minimum, strongly suggests that the mass loss of LBV's at minimum and quiescence is due to radiation pressure.

3. The ratio $\dot{M}$ $v_\infty c/L$ between the momenta of the wind and the radiation is given in Table 1. Its accuracy is about a factor 2 except for R127. This ratio is less than 1, within the errors, for all stars. The mean values are

$$\log \dot{M}\, v_\infty c/L \simeq -1.2 \pm 0.5 \text{ at minimum}$$

$$\log \dot{M}\, v_\infty c/L \simeq -0.4 \pm 0.4 \text{ at maximum}$$

This implies that the acceleration of the wind can be provided by radiation pressure.

4. MULTIPLE SHELL EJECTIONS

In addition to the steady but variable mass loss described in the previous section, several (and possibly all) LBV's eject shells on timescales of the order of months. This is evident from the occurrence of multiple narrow absorption components in the UV and visual absorption lines. Such components have been observed in the spectra of AG Car at -60, -151 and -210 km/s (Wolf and Stahl, 1982), and R81 at -70, -150 and -200 km/s (Stahl et al., 1987).

The velocity variations of the multiple narrow components of the star P Cyg have been studied in detail (de Groot, 1969; Markova and Kolka, 1988; and Lamers et al., 1985). In general three or more violet displaced absorption components can be seen at any moment, sometimes even up to six. The components occur first at low velocities, $-50 \lesssim V \lesssim -100$ km/s, and shift in time to more negative velocities up to -220 km/s. In the v(t) diagrams each component produces a more or less straight line with a slope indicating an acceleration of 0.2 - 0.6 cm/s^2. Each component can be followed during a period of 0.5 - 1.5 yr, during which time the shells travel a distance of 2 - 7 $\times$ 10^{14} cm or 40 - 140 R_*. The repetition time of the shell ejections is 3 - 5 months for P Cygni. Cassatella et al. (1979) estimated that the column density of the shells is typically $N_H \simeq 10^{20}$ cm^{-2} when v $\simeq$ 150 km/s. Assuming a typical distance of 10^2 R_* from the star we find that the mass of a shell is 10^{-7} - 10^{-6} $M_\odot$. If two to four shells are ejected per year, the total mass lost in the shell ejections is smaller than the average mass loss rate, which is 1 $\times$ 10^{-5} $M_\odot$/yr for P Cygni.

Such a detailed analysis has been done for P Cygni only. It suggests that mass loss by multiple shell ejections plays a minor role to the overall mass loss of the LBV's.

5. MASS LOSS DURING ERUPTIONS

η Car: The eruption of η Car in 1837-1860 produced a circumstellar nebula. The core of this nebula, the homunculus, contains 2 $\times$ 10^{-2} $M_\odot$ of dust, which suggest that a total of about 2 - 3 $M_\odot$ was ejected at a velocity of about 700 km/s (see review of Davidson, 1989). The star η Car is also surrounded by "old" ejecta at a distance and velocity which does not agree with an ejection in the previous century. This suggests that η Car has gone through more than one eruption at intervals of several hundred years (Walborn et al., 1978; Davidson et al., 1986).

AG Car: The ring around AG Car suggests the occurrence of one or more ourbursts about 10^4 yr ago with a total mass of about 2 $M_\odot$ (Section 6.1). Previous suggestions that the ring may be due to the interaction between slow matter ejected at a red supergiant phase and the faster wind of the LBV phase are untenable because the new distance determination of 7.1 kpc implies that the star is too luminous to have been a red supergiant. The almost empty region inside the nebula (Paresce, 1989) suggests that no major outbursts have occurred over the last 400 yr if we assume a typical ejection velocity of 700 km/s during an eruption.

P Cyg: The seventeenth century eruption did not leave a visible remnant. The only indication of a remnant is the IR dust emission (6.2) and a radio-arc at a distance of about 0.3 pc (Wendker, 1982; Baars and Wendker, 1987). If the gas-to-dust ratio is 10^2, the total amount of mass ejected in the outburst is on the order of 10^{-2} $M_\odot$.

The evidence for mass ejections in recorded eruptions or in previous major outbursts is summarized in Table 2.

Table 2. Evidence for mass-ejection in eruptions or major outbursts

Star	Remnant	Total Mass ($M_\odot$)	V_{exp} (km/s)	kinematic age (yr)	eruption (AD)
η Car	Homunculus	2-3	700	1.5×10^2	1837-1860
	Old ejecta	--	$\gtrsim 50$	$\lesssim 2\times10^3$	--
AG Car	Ring nebula	2	50	1×10^4	--
P Cyg	30 K dust	10^{-2}	800	4×10^2	1600-1660
R71	140 K dust	3×10^{-2}	20	4×10^2	--

6. THE MASS LOSS HISTORY OF LBV'S DERIVED FROM RING NEBULAE OR CIRCUMSTELLAR MATTER

The presence of circumstellar matter around LBV's, detectable as ring nebulae, extended Hα or [N II] emission or as cold dust may be used to derive the average mass loss rates of these LBV's over the last 10^3 - 10^4 yr.

6.1 Nebulae and Extended Emission

P Cyg: Leitherer and Zickgraf (1987) detected extended Hα and [N II] 6587 emission and showed that this can be explained by a continuous mass loss of 4×10^{-4} $M_\odot$/yr or by multiple shell ejection with $2 \times 10^{-5} < \dot{M} < 1 \times 10^{-4}$ $M_\odot$/yr over the last 300 yr. However, Zickgraf and Stahl (1989) have questioned the reality of the extended [N II] emission around P Cygni, so the results are uncertain.

R127: Stahl (1987) has measured the extended Hα and [N II] 6584 emission (Fig. 3). The emission is roughly circular with a diameter of about 4" = 0.9 pc (Fig. 3). Adopting the measured nebular velocity of 28 km/s and assuming a density of 10^3 cm^{-3} he derived a kinematic age of ~ 1.7×10^4 yr and a total mass of 2.9 $M_\odot$. This corresponds to a mean rate of 1.7×10^{-4} $M_\odot$/yr. Figure 2 suggests that the rate is ~10^{-5} $M_\odot$/yr at minimum and 4×10^{-5} $M_\odot$/yr at maximum. So either the estimated density of 10^3 cm^{-3} is an overestimate or the clumping is more severe than assumed or the mean mass loss rate over the last 10^4 yr has been larger than at present.

AG Car: The ring nebula around AG Car has been studied by many authors (Thackeray, 1956; Johnson, 1976; Stahl, 1987; McGregor et al., 1988; Paresce, 1989). Its average radius is 15" ≈ 0.52 pc, its expansion velocity is 50 km/s and its kinematic age is 1 × 10^4 yr. Assuming the old distance of 2 kpc most authors derived a nebular mass of 0.2 - 0.3 $M_\odot$. Adopting the new distance of 7.1 kpc (Table 1) the mass estimate increases to ~2 $M_\odot$ (Stahl, 1989). This corresponds to a mean rate of $\dot{M} \sim 2 \times 10^{-4}$ $M_\odot$/yr over the last 10^4 yr.

6.2 Circumstellar Dust

R71: Wolf and Zickgraf (1986) detected cold dust around R71 with a temperature of 140 K. This temperature indicates that the dust is at a distance of 8 × 10^3 R_* = 4.5 10^{16} cm. The observed expansion velocity of the circumstellar gas around R71 is 20 km/s, which indicates a kinematic age of the dust region of 400 yr. The dust mass is 3 × 10^{-4} $M_\odot$. Assuming the canonical gas-to-dust ratio of 10^2, the total circumstellar mass is 3 × 10^{-2} $M_\odot$ and the mean mass loss rate is 7 × 10^{-5} $M_\odot$/yr, which is about a factor 3 higher than the rate derived at maximum (Table 1).

P Cyg: Waters and Wesselius (1986) showed that the IRAS observations of P Cyg at 60 and 100 μm indicate the presence of cold dust at T ≈ 30 K. The temperature indicates a distance of 2 × 10^5 R_*. The dust mass is 10^{-4} $M_\odot$ and the total mass is on the order of 10^{-2} $M_\odot$. If this mass was ejected during the eruption of AD 1600, the velocity must have been 800 km/s. This velocity is higher than the typical velocity of 20 - 50 km/s in typical LBV shells, but it is similar to the ejection velocity of the η Car outburst. On the other hand if v ≈ 50 km/s, as for the AG Car nebulae, then the kinematic age is 7 × 10^3 yr and the mean mass loss rate is 1 × 10^{-6} $M_\odot$/yr. This is smaller than the quiescent mass loss rate. So the dust is probably

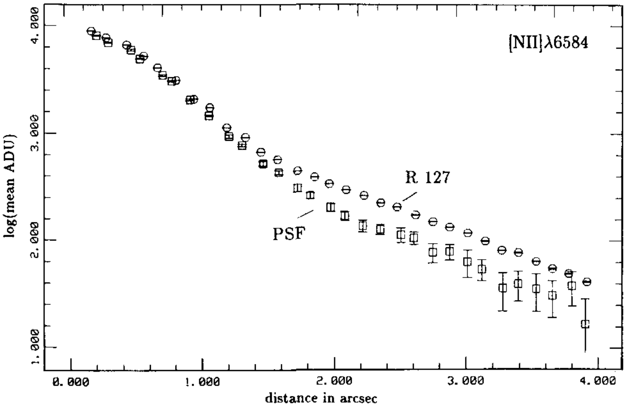

Fig. 3. The radial image profile of the [N II] 6584 line of R127 in digital output units of the CCD versus radial distance from the center. The radial distribution is flatter than that of a point-source (PSF), indicating extended emission around R127, with a mass of 2.9 $M_\odot$ (Stahl, 1987).

formed by the seventeenth century eruption with a total mass of $\Delta M \simeq 10^{-2}\ M_\odot$ if the gas-to-dust ratio is 10^2.

6.3 Conclusion

We conclude that the time-averaged mass loss rates derived from the circumstellar matter around AG Car, R71 and R127 is in the range of 0.7×10^{-4} to $2 \times 10^{-4}\ M_\odot$/yr. The kinematic age of the circumstellar gas is 1×10^4 yr for AG Car and 1.7×10^4 yr for R127.

7. INTEGRATED MASS LOSS AND THE CONSEQUENCES FOR THE EVOLUTION OF MASSIVE STARS

7.1 Time-averaged Mass Loss Rates

The "normal" mass loss rate of the LBV's varies between the values at minimum, $\log \dot{M} \simeq 1.6 \log L - 14.9 \pm 0.5$, and at maximum, $\log \dot{M} \simeq -4.4 \pm 0.2$. Assuming for simplicity that the star spends half the time at minimum and the other half at maximum, we find an average normal mass loss rate of

$$\log \dot{M}_{\rm normal} \simeq -4.7 \pm 0.3 \qquad (1)$$

for stars with $\log L \lesssim 6.3$. The multipole shell ejection does not seem to increase this value significantly.

The mass ejected during eruptions is in the range of 10^{-2} to $2\ M_\odot$. The presence of old ejecta around η Car suggests that eruptions may occur more than once in the LBV phase. The frequency of the eruptions is unknown. The recurrence time is probably larger than 400 yr because P Cygni had its last eruption in 1600-1660. This estimate agrees with the fact that the inner region of the AG Car ring nebula is almost empty (see Section 5) and with the fact that none of the five LBV's in the LMC had an eruption in the last 100 yr. The recurrence time is probably not much longer than 10^3 yrs because the old ejecta around η Car suggest that previous eruptions have occurred several hundred years ago. A recurrence time as large as 10^4 yr is unlikely because of the handful of known LBV's in our galaxy two have suffered eruptions in the last 400 yr. (But, beware of selection effects!) I conclude that the recurrence time of eruptions is probably on the order of 10^3 yr with an uncertainty of a factor 3.

The estimated frequency of the eruptions together with the mass ejected in large eruptions implies an average mass loss rate due to eruptions of

$$-5 \lesssim \log \dot{M}\ (\text{erupt}) \lesssim -3 \qquad (2)$$

This range is consistent with the average mass loss rates derived from study of the circumstellar matter around LBV's (Section 6), which indicates a total average mass loss rate (eruptions plus normal mass loss) of

$$-4.1 \lesssim \log \dot{M}\ (\text{total}) \lesssim -3.7 \qquad (3)$$

for AG Car, R71 and R127. The average mass loss rates may be larger if large eruptions with $\Delta M \sim 1\ M_\odot$ play an important role.

7.2 Evolutionary Consequences

Massive stars with $50 \leq M_i \lesssim 100\ M_\odot$ have to get rid of 5 to 15 $M_\odot$ after the core H-burning before they become a WR star (Maeder and Meynet, 1987). This mass has to be lost in the LBV phase. Adopting the time-average mass loss rate of the LBV's of $\langle\dot{M}\rangle \simeq 10^{-4}\ M_\odot$/yr we find that the duration of the LBV phase is $\tau_{LBV} \simeq 10^5$ yr. The duration may be shorter by a factor 10 if the large eruptions with $\Delta M \sim 1\ M_\odot$ play a dominant role.

This age-estimate can be compared with independent indicators of the duration of the LBV phase. From the ratio between the numbers of LBV and WR stars of $N(LBV)/N(WR) \simeq 10^{-2} - 10^{-1}$ and from the duration of the WR phase of about 5×10^5 yr (Maeder and Meynet, 1987) we find $\tau_{LBV} \simeq 5 \times 10^3 - 5 \times 10^4$ yr. This is lower than the value derived from $\langle\dot{M}\rangle$, but the uncertainties are large.

A more accurate value of τ_{LBV} mimght be derived from the upper limit for the luminosity of the Red Supergiants of $\log L = 5.8$. To prevent stars just above this limit from evolving to the red requires a minimum $\langle\dot{M}\rangle_{LBV}$ which can be transformed into a maximum value of τ_{LBV}.

8. SUMMARY

1. The mass loss rates of LBV's at minimum are in agreement with the predictions for radiation driven winds. The mass loss rates at maximum are about the same for all LBV's at $\dot{M} \simeq 4 \times 10^{-5}\ M_\odot$/yr.

2. Most LBV's are ejecting shells at intervals of months.

3. During eruptions the LBV's eject $10^{-2} - 10^0\ M_\odot$. The recurrence time of the eruptions is uncertain, but it is probably on the order of 10^3 yr.

4. The time averaged mass loss of a few LBV's derived from their circumstellar matter is $10^{-4}\ M_\odot$/yr. The real time-averaged mass loss may be larger if large eruptions with $\Delta M \simeq 1\ M_\odot$ play a dominant role.

5. The duration of the LBV-phase derived from $\langle\dot{M}\rangle$ and the amount of mass to be lost is 10^5 yr or shorter.

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References

Abbott, D.C., Bieging, J.H., Churchwell, E.: 1981, Ap. J. **250**, 645.
Andriesse, C.D., Donn, B.D., Viotti, R.: 1978, MNRAS **185**, 771.
Baars, J.W.M., Wendker, H.J.: 1987, Astr. Ap. **181**, 210.
Cassatella, A. et al.: 1979, Astr. Ap. **79**, 223.
Davidson, K.D.: 1987, in Instabilities in Luminous Early Type Stars, eds. Lamers and de Loore (Reidel), p. 127.

Davidson, K.D.: 1989, these proceedings.
Davidson, K.D. et al.: 1986, Ap. J. **305**, 867.
de Groot, M.: 1969, Bull. Astron. Inst. Netherlands **20**, 235.
Garmany, C.D., Conti, P.S.: 1984, Ap. J. **284**, 705.
Hubeny, I., Leitherer, C.: 1989, these proceedings.
Humphreys, R.M.: 1989, these proceedings.
Humphreys, R.M. et al.: 1984, Ap. J. **278**, 124.
Humphreys, R.M., Lamers, H.J.G.L.M., Hoekzema, N.: 1989, in preparation.
Hyland, A.R. et al.: 1979, Ap. J. **223**, 145.
Johnson, H.M.: 1976, Ap. J. **206**, 469.
Kenyon, S.J., Gallagher, J.S.: 1985, Ap. J. **290**, 542.
Lamers, H.J.G.L.M.: 1986, in Luminous Stars and Associations in Galaxies, eds. de Loore et al. (Reidel), p. 157.
Lamers, H.J.G.L.M.: 1987, in Instabilities in Luminous Early Type Stars, eds. Lamers and de Loore (Reidel), p. 99.
Lamers, H.J.G.L.M., de Groot, M., Cassatella, A.: 1983, Astr. Ap. **128**, 299.
Lamers, H.J.G.L.M. et al.: 1989, these proceedings.
Lamers, H.J.G.L.M., Korevaar, P., Cassatella, A.: 1985, Astr. Ap. **149**, 29.
Leitherer, C. et al.: 1985, Astr. Ap. **153**, 168.
Leitherer, C. et al.: 1989, these proceedings.
Leitherer, C., Zickgraf, F.J.: 1987, Astr. Ap. **174**, 103.
Maeder, A., Meynet, G.: 1987, Astr. Ap. **182**, 243.
Markova, N., Kolka, I.: 1988, Astroph. Sp. Sci. **141**, 45.
McGregor, P. J. et al.: 1988, Ap. J. **329**, 874.
Paresce, F.: 1989, these proceedings.
Pauldrach, A., Puls, J., Kudritzki, R.P.: 1986, Astr. Ap. **164**, 86.
Stahl, O.: 1987, Astr. Ap. **182**, 229.
Stahl, O.: 1989, these proceedings.
Stahl, O., Wolf, B.: 1986, Astr. Ap. **154**, 243.
Stahl, O., Wolf, B., Zickgraf, F.J.: 1987, Astr. Ap. **184**, 193.
Stahl, O. et al.: 1983, Astr. Ap. **127**, 49.
Thackeray, A.D.: 1956, Vistas Astron. **2**, 1380.
van Genderen, A., Thé, P.S.: 1985, Space Sci. Reviews **39**, 317.
van Genderen, A.: 1986, Astr. Ap. **157**, 163.
Viotti, R.: 1988, private communication.
Walborn N.R.: 1977, Ap. J. **215**, 53.
Walborn N.R.: 1982, Ap. J. **256**, 452.
Walborn N.R., Blanco, B.M., Thackeray, A.D.: 1978, Ap. J. **219**, 498.
Waters, L.B.F.M., Wesselius, P.R.: 1986, Astr. Ap. **155**, 104.
Wendker, H.J.: 1982, Astr. Ap. **116**, L5.
White, R.L., Becker, R.H.: 1982, Ap. J. **262**, 657.
Whitelock, P.A. et al.: 1983, MNRAS **205**, 577.
Wolf, B., Stahl, O.: 1982, Astr. Ap. **112**, 111.
Wolf, B., Zickgraf, F.J.: 1986, Astr. Ap. **164**, 435.
Zickgraf, F.J., Stahl, O.: 1989, these proceedings.

DISCUSSION

Sasselov: As I understand it, you interpret the ring nebulae around AG Carinae as actual shells of matter ejected from the star at some time in the past. How are you confident that they are not shock fronts in circumstellar material due to previous continuous mass loss?

Lamers: The new distance estimate for AG Car sets its luminosity well above the upper limit for red supergiants. So AG Car should not have had a previous low-velocity mass-loss phase.

Kahn: Small fluctuations in wind speed can lead to the formation of inhomogeneities at later times. Then *average(density*^{2}) > (*average density*)^2. Ignoring this would lead to an overestimate of $\dot{M}$.

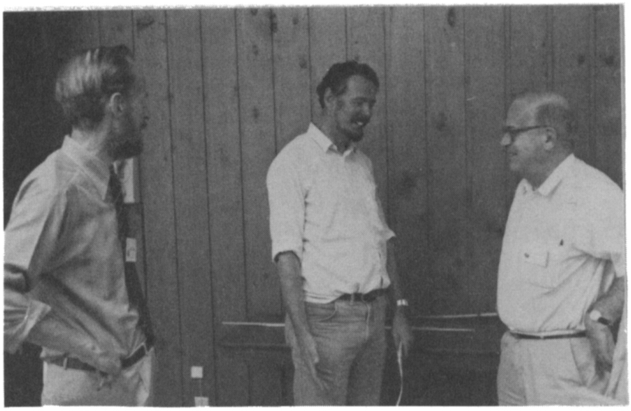
Lamers: This effect was roughly taken into account with a filling factor consistent with Leitherer and Zickgraf's study of P Cygni's Hα emission. The rather large uncertainty in $<\dot{M}>$ derived by Leitherer results from the uncertain clumping and filling factors.

Vanbeveren: In view of the timescales, mass-loss rates, and the apparent enhancement of nitrogen, I think that one has to consider the possibility that an LBV is a normal core-hydrogen-burning star that has gone through an accretion phase (to explain the nitrogen overabundance), with a neutron star or a black hole spiralling into its atmosphere. The few computations of such an event that have been done, do show LBV characteristics.

Davidson: Statistics! We would have to be very lucky or unlucky to know so many examples within historical memory, among such a limited sample of luminous stars.

Henrichs: Regarding the binary scenario that Vanbeveren just mentioned, I notice that if the eclipsing binary R81 should undergo an eruption like R71 for instance, then it would become a Roche-lobe-overflowing system. It seems, however, to be difficult to find the binary nature of LBV's.

Walborn: Concerning η Car and whether it has undergone more than one major ejection event in recent centuries -- Betty Blanco and I have recently discussed third-epoch measurements of proper motions in the outer shell (July 1988: *Publ. Astr. Soc. Pacific* 100, 797). We detected possible decelerations, which, if confirmed, may indicate that all of the material was ejected during the nineteenth-century event. Earlier ejection times have been based on the analysis of plates from just two epochs, necessarily assuming uniform motions.



de Groot, Lamers, Kahn

Walborn, McGregor, Stahl