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WOLF-RAYET STARS IN THE MAGELLANIC CLOUDS. I. THE WN3 BINARY AB 6 IN THE SMC

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ABSTRACT

Moderate dispersion spectroscopy shows AB 6 to consist of a $\gtrsim 6\ M_\odot$ WN3 star in mutual $6^{\rm d}.9$ orbit about a $\gtrsim 37\ M_\odot$ star of type O7. The mass ratio, WR:OB, is low compared to galactic WN binaries of high ionization, although there are no binaries with WN components as hot as this known in the Galaxy. It is possible but unlikely that the low mass ratio may be caused by the inclusion of another unresolved OB star.

Subject headings: galaxies: Magellanic Clouds — stars: binaries — stars: individual — stars: Wolf-Rayet

I. INTRODUCTION

This is the first in a series of papers on detailed studies of Wolf-Rayet (W-R) stars in both Magellanic Clouds (MC). The observational basis is mainly moderate dispersion spectroscopy, starting with the apparently brighter stars.

With metallicity progression $Z \sim 0.003$ through 0.008 to 0.03 for the SMC, LMC, and the solar vicinity of the galactic disk, respectively (Peimbert and Torres-Peimbert 1974, 1976), mass determination of W-R stars based on radial velocity orbits is important in all three galaxies in order to evaluate the influence of heavy element abundances on the advanced evolutionary stages of very massive stars. Observed mass loss rates of galactic W-R stars are so high ($2\text{–}6 \times 10^{-5}\ M_\odot\ \text{yr}^{-1}$ for all subclasses: Barlow, Smith, and Willis 1981) that these stars will lose about half of their mass during the W-R phase ($\sim 3 \times 10^5$ yr), most of which is assumed to coincide with the core He burning stage in the post–main-sequence evolution of massive stars (cf. Vanbeveren 1981). With lower metallicity, the MC stars might be expected to lose mass less rapidly (e.g., Maeder, Lequeux, and Azzopardi 1980), but how much less?

Studies of galactic W-R stars have progressed in recent years moderately well, but they are complicated by two factors: extreme variations in distance and in interstellar extinction. In this respect, the MCs are ideal laboratories to investigate basic properties of such an intrinsically bright group of energetic stars. Not only are the extinctions and their variations from one star to another tolerably small in the MCs (generally $\lesssim$ tenths of a mag), but one can also assume virtually constant, known distance for any member star of either galaxy. Furthermore, neglecting peculiar motions of ~ 10 km s^{-1}, mean radial velocities of different ionic species can be predicted and compared with relative ease in these low inclination galaxies.

No masses are yet available for W-R stars in the MCs. The LMC contains a large, close to completely surveyed sample of 100 W-R stars (Breysacher 1981), ranging in magnitude $V \sim 11\text{–}16$ ($M_v \sim -8$ to -3) if one neglects the bright, diffuse core of 30 Dor, which contains a WN6 component. Only 35% are duplicit according to Breysacher (1981); all occur among the brighter objects. The SMC contains only eight W-R stars (Azzopardi and Breysacher 1979, cited hereafter as AB) with $V \sim 12\text{–}15$ ($M_v \sim -7$ to -4), all of which indicate W-R + OB duplicity, although the spectral lines of an OB component are not explicitly seen in the spectra of three stars. A final consensus of the binary frequency can only be made from a detailed investigation of radial velocity orbits and/or photometric light curves. Only then, with a sufficient data base, can one evaluate with certainty the relative importance of binary mass transfer and stellar wind mass loss in the formation and evolution of W-R stars by the peeling-off process. It is noted that some single-line stars may have low mass, probably compact companions (e.g., Lamontagne *et al.* 1982), while some may be truly single (Vaneveren and Conti 1980).

Admittedly, by starting with the brighter, more readily observed W-R stars in the MCs, one introduces a selection effect in favor of more massive stars and binaries. Thus, it will eventually be necessary to observe a fair sample of the fainter W-R stars, too.

With $V = 12.36$, AB 6 (= 6 in AB's catalogue = R31 from Feast, Thackeray, and Wesselink 1960 and = Sk 108 from Sanduleak 1968) is the second brightest W-R star in the SMC, after HD 5980 = AB 5, which will be the subject of paper II (Breysacher, Moffat, and Niemela 1982). Along with AB 5 and AB 7, AB 6 is located in the northeast section of the main body of the SMC (Ardeberg and Maurice 1979). AB classify it as WN3 + O7 Ia; the spectral classes come directly from the spectrum, while the O star luminosity is based on the bright absolute

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TABLE 1

OBSERVED MEAN AND STANDARD RADIAL VELOCITIES (km s^{-1}) OF THREE SOLAR TYPE STARS

Star	Sp	*RV* (std) ($n = 4$)	*RV* (obs) ($n = 9$)	O − C
HD 6655	G3 IV–V	±15.5 ± 0.5 p.e.	+12.1 ± 3.3 s.e.m.	+3.4 ± 3.3
HD 39194	K0 V	+14.2 ± 0.4	+14.1 ± 2.6	+0.1 ± 2.6
HD 219509	K5 V	±62.3 ± 0.5	+57.4 ± 3.2	+4.9 ± 3.2

magnitude. Walborn (1977) classified it as O6.5(n) + WN3, noting that some absorption lines appear shaded, implying a possible secondary absorption component. This shading is not apparent in the present spectra. This star is particularly interesting since there are no binaries as hot as WN3 known in the Galaxy (Massey 1981).

II. OBSERVATIONS

Thirteen spectrograms of AB 6 were obtained during a 1 week interval in 1978 December and in 1980 January, using the Carnegie image tube on the Yale 40 cm telescope at CTIO, Chile. The inverse dispersion was 43 Å mm^{-1} over 3500–5000 Å in the second order. The S-20 cathode of the image tube necessitated the use of a Schott BG 38 filter to eliminate overlap of undesired orders. The spectra were obtained on baked IIa-O plates. The image tube transfer lens was set at f/1.4. The comparison spectrum was an Fe-Ar hollow cathode. The $2'' \times 9''$ sky supressing slit was rocked in the long direction to give a total spectral width of 0.67 mm. The projected slit was 18 μm wide at the plate. With a seeing of $\lesssim 1''$ during several nights, the intensified image of AB 6 on the slit jaws appeared round and single, indicating the absence of an obvious close visual companion. The star AB 6 is also not located near any apparent star cluster. Of course, this does not guarantee the absence of a second, bright unresolved star in the slit. Exposure times of $\sim$30 minutes produced photographic density near unity for the continuum at the plate center.

Radial velocities were obtained from rectified density scans, using the PDS at the David Dunlap Observatory (cf. Moffat 1978). The wavelength stability of the image tube system was tested on three solar type radial velocity standard stars from the list of Evans (1967) for each of which $\sim$9 spectra were taken on different nights in 1978. Using 14 stellar lines with rest wavelengths drawn from a list at ESO for direct spectra at 73 Å mm^{-1}, which probably corresponds to the present image tube resolution, observed velocities are compared with the standard values in Table 1. The mean O − C is $+2.8 \pm 1.4$ km s^{-1}, which is in the same sense and amplitude expected from the slight, uncorrected curvature of the spectral lines. No systematic variation of radial velocity with telescope position was detected. This high degree of overall reliability reinforces the similar experience reported by Augensen (1979) for the same instrument.

The spectrum of AB 6 is dominated by the broad, moderately weak emission of He II 4685 Å (total width at the base: 3500 km s^{-1}) and the Balmer series absorption lines, for which radial velocities and a journal of observations are given in Table 2. The relative absorption line strengths of He I and He II agree with the O6.5–O7 class of AB and Walborn (1977). The PDS mean of the 1978 spectra (Fig. 1) shows the weak presence

TABLE 2

JOURNAL OF OBSERVATIONS (1978 AND 1980) AND RADIAL VELOCITIES (km s^{-1})

Plate	JD 2,440,000	Emission-Line Phase	He II Emission 4685.682 Å	Mean abs.[a] H 10 − γ
2423 (4)	3840.568	0.635	−69	+26 ± 10 s.e.m.
2429 (4)	3841.640	0.792	−180	+59 ± 24
2433 (4)	3842.561	0.926	−19	+27 ± 7
2439 (4)	3843.565	0.072	+299	−46 ± 3
2445 (2)	3844.562	0.217	+425	−38 ± 5
2451 (2)	3845.568	0.364	+560	−74 ± 17
2456 (2)	3846.563	0.509	+232	+ 8 ± 6
2462 (2)	3847.566	0.655	−148	+34 ± 9
3284 (4)	4254.608	0.982	+396	+26 ± 12
3295 (2)	4256.581	0.270	+503	−38 ± 18
3304 (4)	4258.617	0.567	+184	+ 2 ± 11
3316 (4)	4260.594	0.855	+25	+66 ± 13
3329 (4)	4262.619	0.150	+533	−48 ± 8

[a] After subtracting off the mean for each of the six lines. The overall mean is 178 ± 11 km s^{-1}. (Hϵ is included because the Ca II H *line can be expected to be very much weaker*).

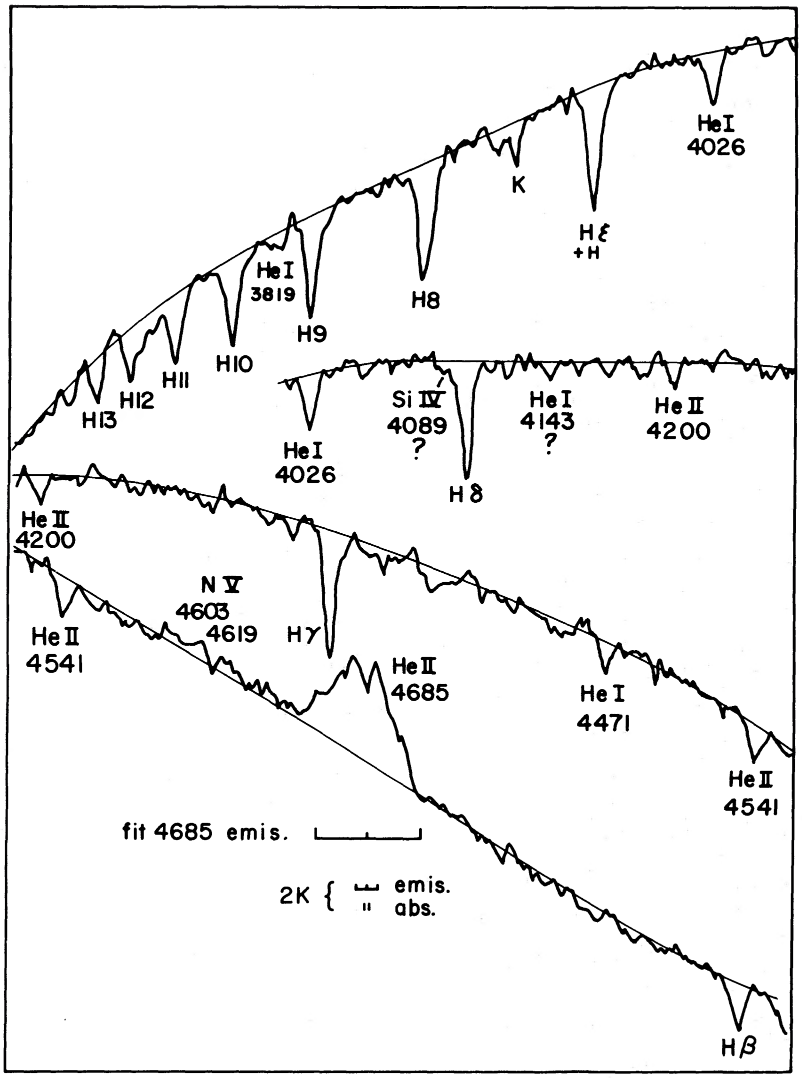

FIG. 1.—Tracing of the mean of the eight 1978 plates after smoothing with a Gaussian filter of FWHM 20 μm

of N v 4604, 4619 Å emission, but absence of N IV 4057 Å emission, in support of the WN3 class of AB 6. Generally, the W-R spectrum tends to be drowned out by the O type component.

In Figure 1 and in the 1980 spectra, the prime luminosity indicator Si IV 4089/He I λ4143 appears to contradict high luminosity (Ia) for the O component (cf. Conti and Alschuler 1971), although this may be caused by lower metallicity in the SMC as indicated for other luminous stars in the MCs (cf. Maeder *et al.* and references therein). In any case these lines are too faint for certain classification. Another hint concerning the luminosity of the O star comes from the weak dip at $\lambda \sim 4685$ Å, superposed on the He II emission line (cf. Fig. 1). A similar dip is marginally visible on the mean of the 1980 spectra. Taken at face value, its strength relative to He II 4541 implies a luminosity class II for the O component, by analogy with galactic counterparts (Conti and Alschuler 1971; Walborn 1973). However, again this feature is too weak to be certain about the luminosity class. Even if it is real, this absorption does not significantly effect the λ4685 emission-line velocities, which were obtained using nearly the full extent in wavelength of the emission, which is ~ 6 times wider than the absorption.

III. RESULTS

Inspection of individual tracings shows no significant temporal profile changes in emission or absorption. Thus, a period search among the radial velocities summarized in Table 2 can be made without fear of distortion. Forcing a sine wave through these data for periods ranging from 5 to 10 days, where the most obvious period must lie, yields the most likely period $P = 6^{\mathrm{d}}.861 \pm 0.005$ with

TABLE 3

ADOPTED CIRCULAR ORBIT AND MASSES FOR AB 6

Parameter	W-R (emission)	OB (absorption)
γ (km s^{-1})	221 ± 30	176 ± 5[a]
K (km s^{-1})	334 ± 42	58 ± 7
E (JD 2,443,000)	843.07 ± 0.14	843.28 ± 0.13
σ_{O-C} (km s^{-1})..............	98	16
$M \sin^3 i/M_{\odot}$	6.4 ± 1.7	37 ± 13
$M_{W\text{-}R}/M_{OB}$	0.17 ± 0.03	

NOTE.—$P = 6^{d}.861 \pm 0.005$; $e \equiv 0$ (see text).

[a] -1.8 ± 4.9 before adding overall mean absorption.

equal probability for the emission and the absorption. With this period, the O − C variance is decreased by a factor of 10 compared to the case for assumed constant velocity. This implies a very high significance for the reality of the periodic variation.

Due to the relatively long time-window (~420 days) between the two sets of data, it is not entirely possible to eliminate periods whose frequencies differ by multiples of $\Delta P/P^2 = 1/420$ day^{-1} from the frequency corresponding to the above adopted, best period. For example, at a multiple of five in either direction from $P = 6^{d}.861$, the variance (O − C) is increased by 43%. The longest alias period related to $6^{d}.861$ is $1^{d}.17$, which leads to a total projected orbital separation $a \sin i = 9.1 \pm 1.0\ R_{\odot}$; for $i \sim 60°$–$90°$ (see below), this leaves little if any space for an O type supergiant. We thus adopt $P = 6^{d}.861$ as the most likely period based on the present observations.

A formal orbital fit to the data in Table 2 yields an eccentricity $e = 0.23 \pm 0.11$ for the emission and $e = 0.17 \pm 0.12$ for the mean absorption; both move in close antiphase. While these may differ from zero, the resulting velocity orbits show suspiciously small scatter at some phases. We therefore adopt a circular orbit as the appropriate solution to the present data. The results of the final orbital fit are presented in Table 3 and depicted in Figures 2 and 3. Emission and mean absorption differ insignificantly from exact antiphase by $0^{d}.21 \pm 0.19$, i.e., close enough to 180° to claim that we are seeing circular orbits of two stars. The O − C standard deviation of the absorption velocities (16 km s^{-1}) is only slightly larger than the internal rms mean error (12 km s^{-1}).

The systemic velocity of the emission line is 45 ± 30 km s^{-1} more positive than the systemic velocity of the absorption lines; this difference is typical for stars of this type in which the relatively strong λ4685 emission line is formed in an accelerating envelope (cf. Lamontagne *et al.* 1982).

The mean systemic velocity for the five best measured Balmer absorption lines is 178 ± 11 km s^{-1}, which is reasonably close to the heliocentric velocity of the main body of the SMC: 163 ± 3 km s^{-1} based on 30 SMC luminous member stars (Ardeberg and Maurice 1979). The difference is only 15 ± 11 km s^{-1} and can easily be explained by normal peculiar velocities. There is also no tendency among the absorption-line γ velocities for a correlation with upper principal quantum number, as might be expected if they are formed in an accelerating photosphere (Hutchings 1976). This indicates that the luminosity and mass loss rate of the O7 component are not extreme.

There may be some doubts, whether the observed Doppler shifts reflect the true orbital motion. In particular, the emission line is formed in outer regions of lower plasma density, where tidal effects and streaming motions could become noticeable. This is unlikely, however, for three reasons: (1) emission and absorption velocities vary in close antiphase; (2) with $a \sin i = 53 \pm 6\ R_{\odot}$, the projected Roche lobe radii are $R_{L,\,W\text{-}R} \sin i = 12.5\ R_{\odot}$ and $R_{L,O7} \sin i = 28\ R_{\odot}$, which are comfortably larger than the estimated stellar radii

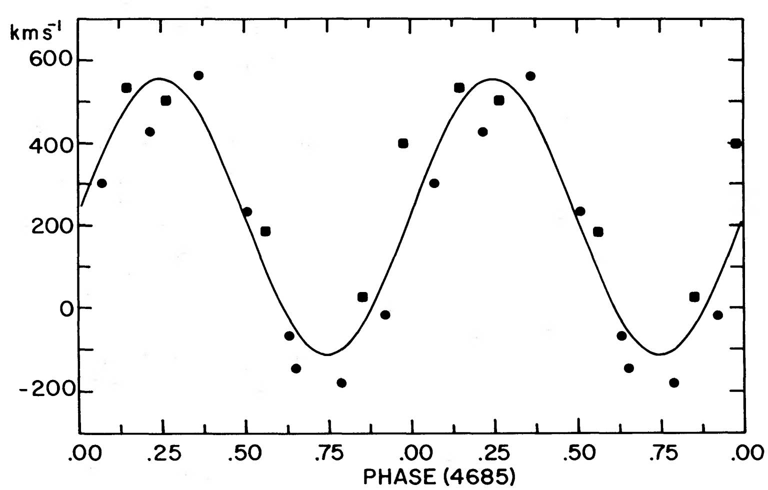

FIG. 2.—Orbital fit to the He II 4685 Å emission-line data using the parameters in Table 3. Circles and squares refer to 1978 and 1980 data, respectively. The total interval over which the 4685 Å line was used to obtain emission-line velocities by parabolic line fitting in rectified spectra is indicated as well as the total orbital amplitudes.

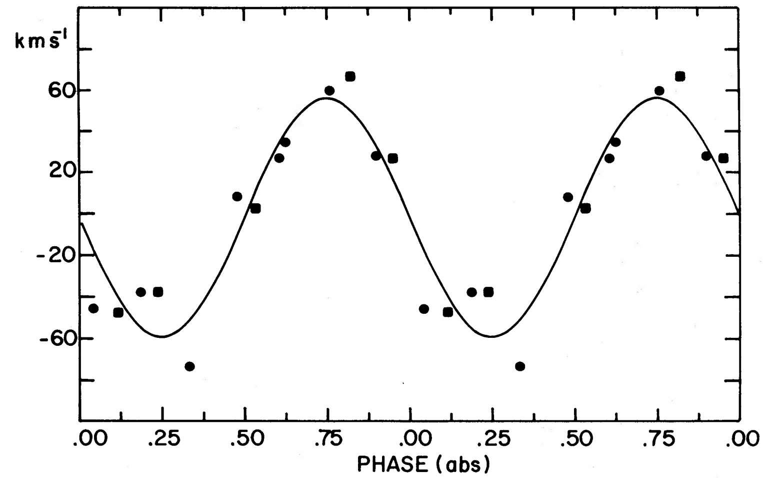

FIG. 3.—As in Fig. 2 but for the mean absorption lines

$R_{WN3} \sim 2\,R_{\odot}$ (Rublev 1975) and perhaps $\sim 10\,R_{\odot}$ for the outer part of the envelope, and $R_{O7I} \sim 15\,R_{\odot}$ (Allen 1973). However, Underhill (1980) estimates the radius of the continuum forming region of early WN stars to be 8–10 $R_{\odot}$. This does not necessarily represent the central star radius; (3) the same trend of large emission-line amplitude relative to absorption amplitude occurs among all of the four other WN3 and WC5 binaries so far observed in the MCs (cf. Moffat 1981), regardless of the periods, which range from $\lesssim 2$ days to $\gtrsim 10$ days.

It is conceivable that the absorption-line amplitude might be reduced by the presence of another unresolved, bright OB star in the system. Lack of phase-dependent profile variations of the absorption lines make this possibility rather unlikely, although higher quality data are needed for a final consensus. The absolute visual magnitude of AB 6 is $M_v = -6.9$ (Walborn 1977). Adopting $M_v = -4.5$ for WN3 (Smith 1973) yields $M_v = -6.8$ for the O component. This is bright compared to the absolute magnitude of a single O7 II star, $M_v = -5.9$, but is comparable to that of a single O7 Ia star, $M_v = -7.0$ (Walborn 1973), allowing for a typical uncertainty for a given star of $\sim \pm 0.5$ mag. We note that the mass function of the W-R star alone (which is impervious to the question of unresolved O stars), $f(m) = 27^{+11}_{-9}\ M_{\odot}$, leads to a low mass ratio ($M_{WR}/M_O < 0.3$) for all values of sin i unless $M_O \geq 50\,M_{\odot}$. Such a high mass is not compatible with the spectral type, especially for low luminosity (cf. Conti and Burnichon 1975), composite or not. Thus, it appears that AB 6 is a W-R + O binary of low mass ratio, in which the O component is probably a supergiant.

IV. SUMMARY AND CONCLUSIONS

A résumé of the adopted orbit, along with the corresponding mass estimates, is presented in Table 3. Since $M_O \sin^3 i$ is already in the right range for O stars, the orbital inclination is probably in the range $i \sim 60°$–$90°$; hence, AB 6 may be a good candidate for showing eclipses. On the other hand, the mass ratio, $M_{WR}/M_O = 0.17 \pm 0.03$, is low compared to *galactic* WNE stars, assuming it not to be the result of blending by another O star. Massey (1981) gives $\langle M_{WR}/M_O \rangle = 0.40 \pm 0.09$ s.d. for six galactic WN4–5 stars. Assuming the masses of all WNE (i.e., WN3, 4, 5) stars in the Galaxy not to differ from one type to another in the mean, this implies that AB 6 is anomalous. The main cause of this would likely be related to the different metallicity, the SMC being about 10 times lower than the solar vicinity. But lower Z implies lower (or at the very least not higher) mass loss rates (cf. Maeder *et al.*), and thus one would expect *higher* mass ratios (W-R/OB) in the SMC, since the W-R star was originally the more massive star. But we observe the opposite, so we reject this hypothesis.

A more plausible but preliminary interpretation may be related to the existence of a mass progression among WN stars, regardless of Z, in the sense that high excitation stars may be relatively less massive than their O companions (cf. Moffat 1981; this contrasts with Massey 1981 based on fewer data). If this is caused by high continuous mass loss in the W-R phase, this implies that WN3 stars would be older than their cooler counterparts. Independent evidence has recently been found for just such an age progression among galactic WN stars based on the nature of the ring nebulae surrounding some of them (Chu 1981).

It is doubtful that the low mass of the WN3 component of AB 6 is the consequence of a longer lifetime for W-R stars in the SMC than the Galaxy since the He-burning lifetime of the W-R core depends only weakly on the metallicity (Vanbeveren 1981). It is also doubtful that conservative mass transfer has been more effective in the SMC; according to De Loore (1981), there is no known model which can produce such low mass ratios at the *beginning* of the W-R phase in massive binaries. Presumably, the high mass loss rates of W-R stars themselves must play the dominant role. A final discussion on these points is postponed to a later paper in this series.

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