THE GALACTIC WN7/WN8 STARS AS MASSIVE O STARS IN ADVANCED STAGES OF EVOLUTION

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ABSTRACT

It is shown from various observational contraints that WN7/WN8 stars tend to occupy a class of their own set apart from other Wolf-Rayet subclasses. They probably evolved by stellar-wind mass loss from Of stars with original masses greater than ~35 $m_\odot$, whether single or component of a binary. Two WN7/WN8 stars may be runaways in the second WR phase. One, HD 197406, is situated over 1000 pc from the galactic plane and has a low-mass, overluminous companion which is eclipsed by the WN7 component.

1. COMPARISON OF WN7/WN8 WITH OTHER SUBCLASSES OF WR STARS

Observationally there are at least five factors which set WN7/WN8 stars apart from all other subclasses of Wolf-Rayet stars, whether WN4-6 or WC5-9:

(1) The main difference occurs in *intrinsic luminosity*: with $M_v = -6.8$ (-6.2) for WN7 (WN8) they are two full magnitudes brighter than other WR stars with mean $M_v = -4.4 \pm 0.4$ (max) according to the calibration of Smith (1973). The same trend persists for the bolometric absolute magnitudes while the effective temperatures of the WN7/WN8 stars lie at the hot end of the remaining WR stars (Conti, 1976).

(2) WN7/WN8 stars appear to be *younger* on the average than other WR stars. From the association of 19 galactic WR stars with 17 open clusters (Moffat and Seggewiss, 1978) six WN7/WN8 stars belong to clusters with mean earliest spectral type O4 ± 1 (s.d.) while 13 WR stars of other type belong to clusters of type O8 ± 2 (s.d.). This implies a total mean age of $\sim 3 \cdot 10^6$ a for WN7/WN8 stars and $\sim 5 \cdot 10^6$ a for other WR stars.

(3) Morphologically, the *spectra* of WN7/WN8 stars always show narrower lines than earlier WN stars. However, while

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their lines are wider and more developed, the spectra of WN7/WN8 stars resemble Of stars more than any other of the WR subclasses. This is born out in Fig. 1 which shows photographic transmission tracings at coudé dispersion of the six brightest WN7/WN8 stars in the sky along with a typical WN6 and an extreme Of star. Especially noticeable is the N IV 4058 emission line which is relatively narrow and unblended in the WN7/WN8 spectra unlike the WN6 spectrum where it is broad and asymmetric. It is absent in the Of spectrum. Evidence is also accumulating for the existence of transition types between Of and WN7/WN8 stars (e.g. the undermassive Of star components in the spectroscopic binaries BD +40°4220 (Bohannan and Conti, 1976) and HD 228766 (Massey and Conti, 1977) and a sequence of five stars ranging from O through Of to WN8 in a newly discovered southern cluster (Havlen and Moffat, 1977)).

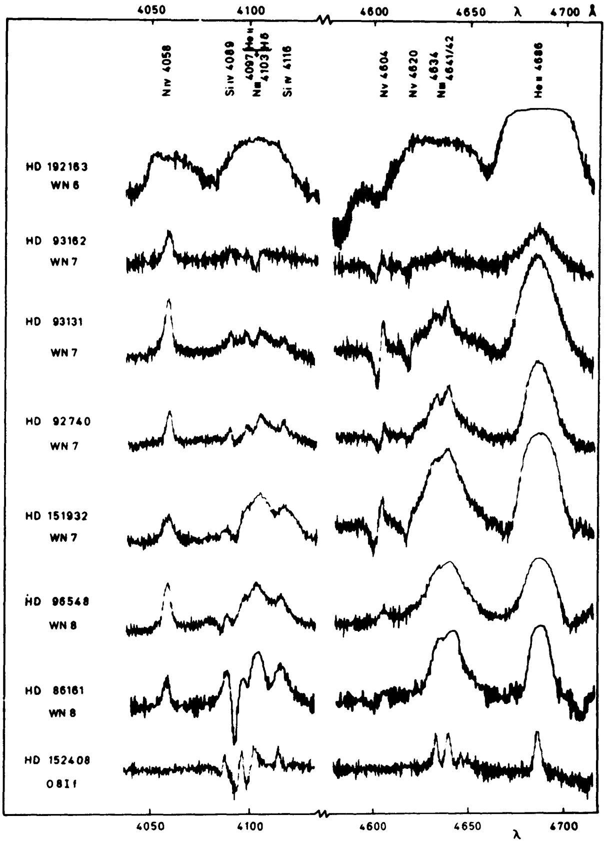

Fig. 1. Photographic transmission tracings (4040-4130 Å and 4580-4710 Å) of a sample of stars ranging in spectral type from WN6 through WN7, WN8 to an O8f supergiant.

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(4) The *ionization/excitation structure of the envelopes* of WN7/WN8 stars is dramatically set apart from the remaining WN stars. This is demonstrated in Fig. 2 where we see a much more rapid increase of expansion velocity with potential of violet shifted absorption lines for the WN7/WN8 stars. Again there appear to be no transition stars between WN6 and WN7.
(5) Another point of contrast concerns *abundance differences*. The ratio by number of H/He, compared to the mean cosmic value of 10, is ≳1 for the WN7/WN8 stars and drops dramatically to 0.00-0.14 for the remaining WN subclasses (Smith, 1973; Rublev, 1975). WC spectra are too complex to allow a useful estimate.

Taken all together, the above arguments strongly suggest that the WN7/WN8 stars have evolved from luminous progenitors of higher mass than all other WR subclasses. This agrees well with the theoretical calculations and predictions of Chiosi

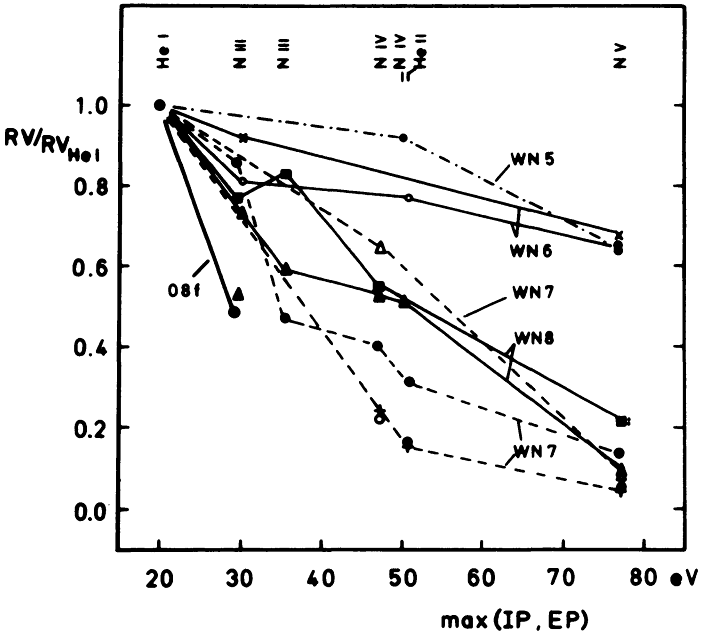

Fig. 2. Ionization/excitation structure of the envelopes of WN5, WN6, WN7, WN8 stars and an O8If star. The radial velocities RV of the violet shifted absorption edges have been reduced to unity for the He I lines which have the lowest potential and are assumed to be formed in the outermost region of the envelope where the maximum expansion velocity is attained. The abscissa is the maximum of the ionization or excitation potential for the line concerned (cf. Smith and Aller, 1969).

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et al. (1978) who claim parent masses for WN7/WN8 stars of $\gtrsim 35-40\ m_\odot$ but only $\sim 30\ m_\odot$ for the remaining WR classes. In view of the distinct magnitude gap in the HR diagram and the lack of transition WN6-WN7 types it appears doubtful that WN7/WN8 stars evolve into earlier type WN or into WC stars. If they in fact do, then the transition must occur very rapidly.

2. STATISTICS OF WN7/WN8 STARS AND COMPARISON WITH O STARS

Using the catalogue of Smith (1968a) as a basis we present in Table 1 a complete list of known galactic WN7 and WN8 stars (for notes to individual stars cf. Moffat and Seggewiss, 1978). Some spectral types have been revised and a few stars added or deleted. The distances are based on the study of galactic WR stars by Smith (1968b) who assumed the same absolute magnitudes for WN7 and WN8 stars as noted in section 1.

Taking a distance of 3 kpc from the sun to represent the radius of completeness for the discovery of galactic WR stars (Stenholm, 1975) we find

$$n(\text{WN7/WN8})/n(\text{other WR}) = 5/31 = 0.16$$

in which the statistics of the other WR stars were taken again from Smith (1968b) with revised absolute magnitudes where necessary (Smith, 1973). Theoretically, one can calculate the ratio to be expected from two assumptions:
(a) the number of progenitor stars obeys a universal initial mass frequency function

$$n(m) \sim m^{-2.35} \qquad \text{(Salpeter, 1955) and}$$

(b) the representative mass of a WN7/WN8 progenitor is $\sim 50\ m_\odot$ and $\sim 30\ m_\odot$ for other WR stars with mean duration of the (He-burning) WR phase of ~ 3 and $\sim 5 \cdot 10^5$ a, respectively (Chiosi et al., 1978).

Thus one expects a ratio of $(3/5) \cdot (30/50)^{2.35} = 0.18$, compatible with the observations.

Since Of stars and WN7/WN8 stars have nearly the same absolute visual magnitudes in the mean (Conti, 1976) we can compare their number density directly using apparent magnitudes. From the catalogue of 130 O stars with high quality spectral types of Conti and Alschuler (1971) there are 46 galactic Of stars north of declination $\delta = -20^\circ$. For the same limit of completeness ($V \leq 8.0$) and declination range there are four stars of type WN7/WN8; thus

$$n(\text{WN7/WN8})/n(\text{Of}) = 0.09.$$

A ratio of this order is also expected if all Of stars (i.e. O stars with $m \gtrsim 35\ m_\odot$) become WN7/WN8 stars

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Table 1. Catalogue of all known galactic WN7/WN8 stars

HD/name	MR	Sp	v	l	b	d	r	z
						kpc	kpc	pc
86161	19	WN8	$8^{m}.43$	$281^{\circ}.1$	$-2^{\circ}.6$	4.0	10.0	- 181
92740	25	WN7	6.44	287.2	-0.8	2.9	9.6	- 40
93131	28	WN7	6.49	287.7	-1.1	3.5	9.5	- 67
93162	29	WN7+O7	8.17	287.5	-0.7	4.4	9.6	- 53
MS 3	-	WN7-8	12.67	288.6	-1.0	17.4	17.1	- 304
-	32	WN8+OB	10.88	289.8	-1.2	7.9	10.4	- 166
96548	34	WN8	7.85	292.3	-4.8	4.0	9.3	- 333
117688	49	WN7	10.87	307.8	+0.2	12.0	9.8	+ 42
134877	54	WN8	11.71	320.1	-1.8	7.6	6.4	- 238
151932	64	WN7	6.61	343.2	+1.4	2.3	7.8	+ 56
LS 11	-	WN7	12.42	341.9	-2.4	11.0	3.4	- 459
LSS 4064	-	WN8+OB:	(12.0)	348.7	-0.8	2.9	7.2	- 40
LSS 4065	-	WN8+OB	(11.0)	348.7	-0.8	2.9	7.2	- 40
-	89	WN7	(11.94)	27.8	+0.2			
177230	91	WN8	(11.1)	30.5	-4.8	9.4	5.1	- 787
M1-67	-	WN8	(11.1)	50.2	+3.3	4.3	8.0	+ 250
LS 16	-	WN8:	(13.7)	68.2	+1.0			
-	97	WN7	12.30	69.9	+1.7	1.0	9.7	+ 31
228766	105	WN7+O	9.33	75.2	+1.0	5.0	10.0	+ 87
-	111	WN7:	(10.5)	79.7	+0.7			
197406	113	WN7	10.50	90.1	+6.5	9.1	13.5	+1032
214419	118	WN7+O7	8.94	105.3	-1.3	5.8	12.8	- 130
-	119	WN8	11.18	109.8	+0.9	4.6	12.3	+ 72
-	122	WN7	11.49	115.0	+0.1	6.9	14.4	+ 12

Notes:

MR = no. in the catalogue of Roberts (1962)
d = distance from the sun
r = galactocentric distance
z = distance from the galactic plane

(assumed to be He stars of $m \gtrsim 10\ m_{\odot}$) and their respective mean life times are $\sim 3\cdot 10^6$ a and $\sim 0.3\cdot 10^6$ a.

Another important observational quantity is the relative number of binary to single WN7/WN8 stars. From Smith's (1968a) catalogue of WR stars, the number ratio of single-line stars to spectroscopic binaries for all WR subclasses is nearly unity for $v \leq 10.5$ and increases dramatically (and therefore spuriously) for fainter stars whose spectroscopic data are progressively less complete (the ratio is

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~10 for v ≥ 11). Therefore, we have made a list (Table 2) of all galactic WN7/WN8 stars for v ≤ 10.5 separated according to their spectroscopically proven single or binary nature (for notes cf. Moffat and Seggewiss, 1978). One sees that the binary frequency among galactic WN7/WN8 stars is close to 50%. This compares well with the binary frequency among O stars (including Of) which is 58% according to Conti et al. (1977). This similarity is again strongly suggestive of a common origin of all WN7/WN8 stars from massive Of stars; whether single or binary appears to make little difference.

Table 2. List of single and binary stars among a complete sample of WN7/WN8 stars with v ≤ $10^m.5$. The mass function f(m) refers to the velocity of the WR component whose mass m_{WR} was assumed to be 10 $M_\odot$ except for HD 228766 where both masses were observed separately. (All masses are in solar units.)

Single stars (RV constant)

HD	Sp	Notes
86161	WN8	1
93131	WN7	2
93162	WN7	3
96548	WN8	1
151932	WN7	4

Proven binary stars (RV orbit available)

HD/name	Sp	Type	P	f(m)	i = 90° m_{WR}	i = 90° m_2	i = 60° m_{WR}	i = 60° m_2	Notes
92740	WN7	SB1	$80^d.35$	1.67	10	8	10	10	2
228766	WN7+O	SB2	10.7424	4.24	16	16	24	25	5
MR 111	WN7:	SB1	22:	7.7	10	18	10	24	6
197406	WN7	SB1	4.3207	0.251	10	3.6	10	4.3	7
214419	WN7+O7	SB1	1.64	4.38	10	14	10	17	8

3. KINEMATICS AND DISTRIBUTION OF GALACTIC WN7/WN8 STARS

It is fortunate that, unlike the other WR subclasses, the WN7/WN8 stars have some narrow, symmetric emission lines whose positions yield velocities close to the systemic velocity. In particular, the emission line of N IV λ4058 has the additional advantage that it is unblended. This line is generally not seen in Of stars whose emission spectrum is not as strongly developed.

In Table 3 we present a compilation of 11 WN7/WN8 stars for which reliable radial velocities are available, mostly based on the emission line of N IV λ4058. Neglecting M1-67 and HD 197406 which may be high velocity stars, the mean difference between observed radial velocity RV(4058) and expected velocity RV(rot) due to differential, circular galactic rotation and peculiar solar motion for the nine remaining stars is

$$RV(O-C) = -15 \pm 13 \text{ (s.d.) km s}^{-1}.$$

This difference probably reflects the small systematic effect of line asymmetry in an expanding envelope. However, agreement is sufficiently good to indicate that the distances and absolute magnitudes on which the comparison is made are probably quite reliable. Applying this as a correction, we find that M1-67 has a residual, peculiar radial velocity of 184 km s^{-1} and HD 197406 has -35 km s^{-1}.

Table 3. WN7/WN8 stars with reliable velocities

HD/name	Sp	l	RV(4058)	RV(rot)	ΔRV
			km s^{-1}	km s^{-1}	km s^{-1}
86161	WN8	281°	- 23	+ 9	- 32
92740	WN7	287	- 23	- 6	- 17
93131	WN7	288	- 38	- 7	- 31
93162	WN7	288	- 26	- 4	- 22
96548	WN8	292	- 16	- 15	- 1
151932	WN7	343	- 48	- 28	- 20
M1-67	WN8	50	+207*	+ 38	+169
228766	WN7+O	75	- 10	- 12	+ 2
197406	WN7	90	-126	- 76	- 50
214419	WN7+O7	105	- 75	- 60	- 15
MR 119	WN8	110	- 50*	- 50	0

* N IV 4058 velocity not available; value based on other narrow lines.

The overall distribution of WR stars projected onto the galactic plane has recently been studied by Smith (1973) and Stenholm (1975). While there is some correlation with local spiral features, the overall correlation in the galaxy suffers from the lack of precision in single-star parallaxes.

In Fig. 3 we show a plot of perpendicular distance z from the galactic plane versus galactocentric distance r for WN7/WN8 stars of known distance. Restricting to r = 10 ±4 kpc and omitting M1-67 and HD 197406 (MR 113) which are probably high velocity stars and HD 96548 (MR 34) whose absolute z-value is even larger than that of M1-67, we find

$$\overline{|z|} = 89 \text{ pc},$$

much like the mean z found for the local, young population I OB stars: 80 pc (Gunn and Ostriker, 1970).

With z = +1032 pc (i.e. >10 times larger than the average |z|) HD 197406 may be a runaway star with the main part of its velocity vector directed perpendicular to the galactic plane; its systematic radial velocity component also differs by ~35 km s^{-1} compared to that expected from normal differential galactic rotation. On the other hand, M1-67 may be a runaway star with most of its velocity vector directed in the plane. There may be one or more other runaways in the sample of WN7/WN8 stars but their velocities and separation from the galactic plane do not appear to make them stand out like HD 197406 and M1-67.

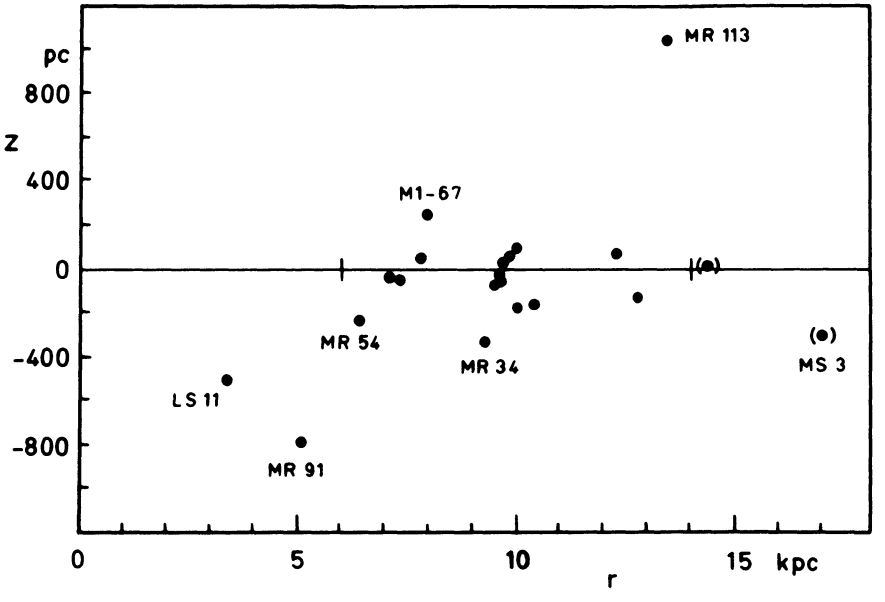

Fig. 3. Galactic distribution of WN7/WN8 stars: distance z perpendicular to the plane versus galactocentric distance r. The sun is assumed to lie 10 kpc from the galactic centre. Brackets indicate less reliable data. The vertical bars at r = 6 and 14 kpc indicate the limits posed for discussion.

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In the context of possible runaway stars, it is interesting to compare with the O stars (Conti et al., 1977). Taking runaways to be those stars with RV(pec) > 40 km s^{-1} or $|z| > 300$ pc we find, from a sample of 87 O stars with reliable radial velocities 11% ± 4% runaway suspects (10 stars). Among our sample of 17 WN7/WN8 stars with r = 10 kpc ± 4 kpc we find the percentage to be 18% ± 10% (3 stars). These numbers overlap, again in support of the common origin of WN7/WN8 and (massive) O stars.

4. EVOLUTIONARY STATUS

From the preceding sections it appears very likely that most, if not all, WN7/WN8 stars evolve directly by stellar-wind mass loss from massive O-star progenitors. Perturbations due to binary mass transfer may speed up the process but are unlikely to be decisive. Support for this is found from direct observations of high mass loss rates among Of stars (Barlow and Cohen, 1977) and by the presence of expanding rings of thermally excited H II gas surrounding some single WN stars (cf. Smith, 1973).

Additional complications may occur in the evolution of massive stars to produce runaway WN7/WN8 stars, at least in the case of HD 197406 and M1-67. We postulate that these stars are in the second WR phase after having been accelerated to high velocities by a supernova explosion of the original primary in a massive binary system (cf. van den Heuvel, 1976). This is much like the explanation put forth to explain the runaway OB stars (cf. Bekenstein and Bowers, 1974) except that the massive runaway OB component has evolved by stellar-wind mass loss into a WN7/WN8 star.

Of particular interest is the WN7 star HD 197406 for which there is sufficient data available to make the above suggestion very plausible. Not only is it located further from the galactic plane than *any* other WR star (cf. Fig. 10 of Stenholm, 1975) and it has a moderately peculiar radial velocity, it is a single-line spectroscopic binary with a low mass function (cf. Table 2). Using the gravitational force law perpendicular to the galactic plane derived by Oort (1965) and a probable time ($\sim 5 \cdot 10^6$ a) elapsed since the supernova explosion occurred while the system was situated in the galactic plane, it is possible to calculate the original (Z_o) and present (Z) z-velocity components necessary to have reached the present distance from the galactic plane, z = 1032 pc. We obtain Z_o = 207 km s^{-1} and Z = 198 km s^{-1} which are at the high end of the peculiar radial velocities observed for runaway OB stars ($\sim$200 kms^{-1}) by Bekenstein and Bowers (1974). For comparison, M1-67 has

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an observed peculiar radial velocity of +184 km s^{-1} but little is known about its possible binary nature.

A possible scenario for HD 197406 might be the following: Let as start with a binary WR system in the galactic plane just before the supernova explosion. The system has eccentricity e = 0 and period P = 2 d similar to the WN7+O7 binary HD 214419. Let the WR component have a mass of ~24 $m_\odot$ similar to the WN7 component of HD 228766 for a likely orbital inclination i = 60° and the O star companion a mass of 35 $m_\odot$, the minimum to produce the *present* WN7 star. Then, following Sutantyo (1973) for an assumed instantaneous symmetric supernova explosion we indicate schematically in Fig. 4 a possible scenario. The final period and eccentricity are assumed to match the presently observed system, and represent plausible values after tidal circulization of the eccentric post-supernova orbit.

Stage	$m/m_\odot$	WR	O star	$m/m_\odot$	P(d)	e	z(pc)	Z(kms^{-1})
Start	24			35	2	0	0	0
Post SN	4	compact		35	7.2	0.51	0	200
After $5 \cdot 10^6$a (now)	4		WN7	10	4.3	0	1000	190

Fig. 4. A possible scenario for HD 197406

Further supporting evidence comes from the light variations of HD 197406. Fig. 5 presents the light and colour curves taken from the data of Bracher (1966), While the colour b-v remains constant with phase, the magnitude v varies systematically with phase (with some additional intrinsic noise) with an amplitude ~0.045. Minimum light occurs near phase 0.5 when the WR component is in front.

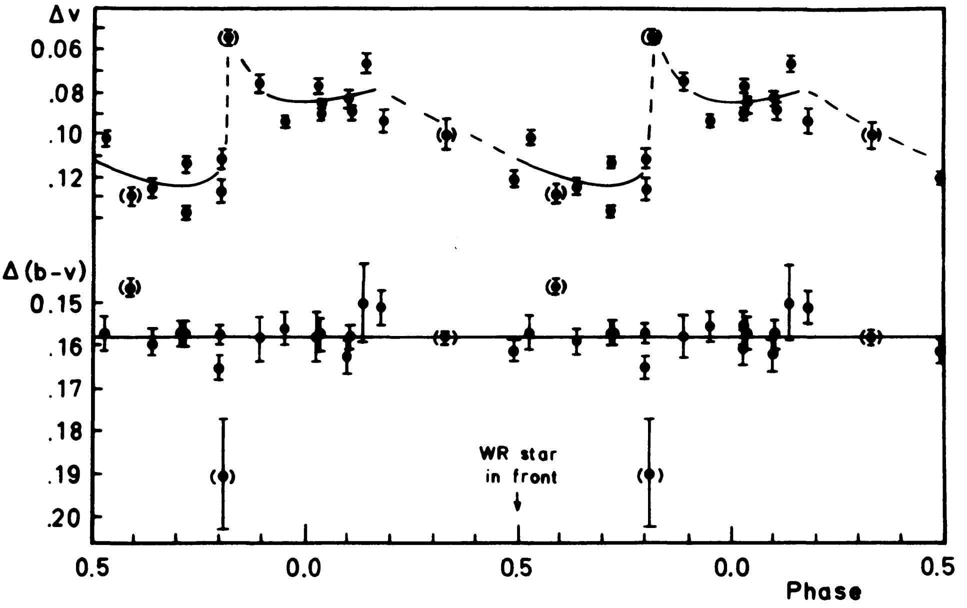

Fig. 5. Light curve of HD 197406 based on the original data of Bracher (1966). Visual magnitude and colour differences refer to HD 197406 minus BD +52° 2774 obtained during two runs in 1964 and 1965. Each point is the mean of from 9 to 20 individual measurements (3 or 4 measurements only for bracketed values) while the bars are the length of 2σ where σ is the internal standard deviation for each point. Fitted curves are best eye estimates.

The light variation is likely not due to ellipsoidal variation in view of the lack of two clear minima per cycle. Nor can it be due to oscillations of a dense He star (the WR component) which would be of the order of an hour (Stothers and Simon, 1970), not days as observed. This leaves as most plausible explanation the variation of light (directly or indirectly) mainly from a second star orbiting the WR component. In order to yield the observed visual amplitude, the unseen star must have an effective absolute magnitude $M_v \leq -3.4$ which is equivalent to a star at least as bright as an unreddened B1V star with luminosity $L_2 \sim 2 \cdot 10^{37}$ erg s^{-1}. Such a star would be much too massive to explain the observed low mass function. The most plausible explanation is that the secondary is a compact star which, by the process of mass accretion in the WR envelope, would appear overluminous for its mass. Such a star would be a result of the supernova explosion that accelerated the star to its present high z-value. From the orbit of HD 197406, this compact star would be revolving well within the WR envelope that, even when the star is on the near side, would almost entirely degrade the X-radiation into photons of longer wavelength (cf. Moffat and Seggewiss, 1978). Although there is no information available on HD 197406 in the UV, it has no detectable IR excess compared to other WN7 stars (Hackwell et al.,1974). However, the optical light curve may be a result of the modulation of the degraded source as it orbits in the dense WR envelope. The constant colour would then be a result of wavelength-independent electron scattering, the principle source of opacity in the envelope.

The search for other candidate runaway WR stars is continuing. In fact Firmani (1978) has recently found evidence that the WN5 star HD 50896 is probably such a star.

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DISCUSSING FOLLOWING MOFFAT and SEGGEWISS

Bisiacchi: If I remember well the calculation of Bekenstein and Bowers, if the binary system is not disrupted by the supernova explosion, you cannot obtain the velocities necessary to put the star at that distance from the plane.

Moffat: Indeed Bekenstein and Bowers (1974) state that most OB-runaway velocities will lie in the range 30-50 km s^{-1} after receiving a kick from a SN explosion but exceptional cases can lead to values up to ~ 200 km s^{-1} in very close, very massive binaries, i.e. enough to get a star out to z ~ 10^3 pc in ~ 5 10^6 years. Indeed, observed radial velocities of OB runaways range up to ~ 200 km s^{-1}.

Van Blerkom: Tademaru has proposed a "tugboat" model in which a newly formed, rapidly rotating neutron star is accelerated to high velocity by asymmetric emission of radiation and pulls its companion along with it. This could account for a runaway without disruption of the binary system.

Moffat: But admitting the presence of a neutron star companion already implies a runaway system due to the violent process of formation of the neutron star in the first place. The "tugboat" will only help increase the acceleration if its momentum vector is pointing in the right direction.

Vanbeveren: I just want to mention that starting with a 35 M_0 star including a stellar wind phase, will end up with considerably higher masses ($\pm$ 18 M_0).

Moffat: Indeed, but this 18 M_0 WN7 star will by virtue of its very high mass loss rates, evolve to a smaller mass, say ~ 10 M_0, the mean value observed for WR components in known binaries.

Massey: Did you redo the orbit, or were your comments on HD 197406 based on Katherine Bracher's orbit determination? The reason for asking is that I think I recall that the mass function was uncertain by a factor of ~ 4, depending on which emission line was used.

Moffat: All data shown for HD 197406 are from Bracher's thesis (1966). We took her mass function for the NIV 4058 line which is the most symmetrical, weak, unblended emission line: f(m)=0,251 M_0. This is a conservative way not to push the unseen star's mass down too far. Bracher had adopted f(m)=0.07 M_0 which would make our case of a low mass companion even stronger.