SESSION 4

OBSERVATIONS OF WOLF-RAYET BINARIES

Chairman: A.TUTUKOV

Introductory speakers: P.MASSEY
A.F.J.MOFFAT

1. K.A. VAN DER HUCHT, P.S.CONTI and A.J.WILLIS: The iron curtain of WC9 stars.
2. R.LAMONTAGNE and A.F.J.MOFFAT: A spectroscopic search for duplicity among a complete sample of northern WR stars.
3. I.LUNDSTROM and B.STENHOLM: Is HD 164270 a long-period eclipsing binary ?
4. V.S.NIEMELA and R.H.MENDEZ: A spectral study of HD 50896.
5. V.S.NIEMELA: Observations of new WR binaries.
6. P.PISMIS and A.QUINTERO: The velocity field of S308: the ring nebula around the WN5 star HD 50896.
7. F.BEECKMANS, C.A.GRADY, F.MACCHETTO and K.A. VAN DER HUCHT: Spectral variations of Theta Muscae (WC6+O9.5I) in the UV.
8. J.BREYSACHER, A.F.J.MOFFAT and V.S.NIEMELA: The WR eclipsing binary HD 5980 in the Small Magellanic Cloud.

WOLF-RAYET STARS WITH MASSIVE COMPANIONS

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I. INTRODUCTION

The study of Wolf-Rayet binaries is important for the information we can gleam about the most fundamental property of any star: its mass. In this regard we are very fortunate, since the masses of WR stars can be determined with far greater confidence than can their luminosities, compositions, colors, effective temperatures, etc. By simply measuring the velocities of both components in a WR+O system, we can find the minimum masses and the mass ratio of the two stars; if we can get some further handle on the orbital inclination, we then know the mass of the WR star directly.

Most of the early studies of WR stars were confined to the WR+O binaries. Since the stars are very massive and the periods short, spectacular changes in the velocities of the emission lines were often visible from night to night. (This is not true for O+O systems, since their mass ratios are closer to unity, and the absorption lines of the two stars are often blended together.) In the 1940's and early 1950's, many of the northern hemisphere WR binaries were discovered and studied by W.A. Hiltner and O.C. Wilson. In her thesis, K. Bracher (1966) added new data for a few stars, and recomputed the orbital elements for all the systems using modern techniques; her discussion nicely summarizes the earlier work and will not be repeated here. Most of these systems had been studied at low, prismatic dispersions. As these systems have been reexamined in the last few years at higher dispersions, we have found that the older emission-line velocity curves hold up very well, although significant improvements have been made in the absorption-line velocity curves. For a few systems, high dispersion studies have proven to be <u>essential</u> for the (hopefully) correct qualitative understanding of their nature: e.g., HDE 228766 (Massey and Conti 1978), θ Mus (Moffat and Seggewiss 1977), and HD 211853 = GP Cep (Massey 1981a).

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The most dramatic improvement in our knowledge of WR masses since the last IAU symposium has come from the many new orbit solutions for the southern WR binaries, due primarily to the long-term efforts of V.S. Niemela and collaborators. Since telescope time in the southern hemisphere remains at a premium, many of these systems have had to be studied at lower dispersions than those in the north; even the orbit of γ Vel, a second magnitude star, is based primarily on cassegrain data (Niemela and Sahade 1980). However, these efforts have at least begun to bring the study of the southern systems on to a par with those in the north.

In this review, I will try to summarize the conclusions that can be drawn for the WR stars with massive companions. For the most part, these systems are "double-lined" (SB2's) in which the absorption spectrum of the O star companion is present and moves in the opposite sense than the WR emission lines. For a few cases, the WR star is sufficiently brighter than its companion that the O spectrum is not present in the visible region, although the mass functions of these "single-lined" (SB1's) systems still implies a massive companion. The WR stars with alleged low mass companions will be summarized elsewhere in this symposium by Moffat.

II. THE PHYSICAL PARAMETERS OF WR+O SYSTEMS

A. The Companions

Most of the WR binaries with massive companions are SB2's, which is consistent with what (little) is known about the absolute luminosity of single WR stars (e.g., Conti 1979 and this symposium). For the absorption spectrum of the companion to be invisible, the WR star would need to be about a magnitude or so brighter than the companion; since the absolute magnitude of most WR stars are comparable to, or slightly less bright than, most O stars, it is not surprising that the companions are visible in almost all cases. The exceptions are mainly found among the late WN stars, some of which are known to have high absolute luminosity. The WN6 star HD 193928 was studied by Bracher (1966); absorption lines were not visible, but it is possible that better S/N data might detect the companion. The WN7 star MR13 discussed by Niemela at this symposium also shows no sign of its companion. Two other WN7 stars, HD 92740 and CQ Cep, show absorption spectra which are intrinsic to the WR star itself, since these lines move in phase with the emission; the companion in each system is thus the less bright member, and its detection is additionally complicated by the need to resolve its lines from those of the Wolf-Rayet (Conti, Niemela, and Walborn 1979; Niemela 1980). For HD 92740 there is a possible detection of the O star's lines (Conti, Niemela and Walborn 1979); I have retained it as a SB1 since the authors remained dubious. For CQ Cep, a faint absorption feature near He II λ 4686 emission moves in opposite phase to the emission (Niemela 1980); I have arbitrarily included this as an SB2, although additional work is badly needed to substantiate the companion's orbit. The WC6 binary θ Mus shows a beautiful absorption spectrum; unfortunately, these lines are stationary, suggesting either an unusual mass ratio, or, (more likely!) that a third star is present which dominates the absorption line spectrum. (Moffat and Seggewiss 1977).

The magnitude differences in WR+O systems are easily understood from what we know about the mass ratios of O+O systems. As C.D. Garmany has shown, the mass ratios in O+O binaries are nearly always unity, with few, if any, systems having mass ratios greater than 3 (Garmany 1979; Garmany, Conti and Massey 1980). As the stars evolve they lose mass, with the (initially) higher mass star evolving the fastest and losing the most mass in the process. Once the mass ratio of the system approaches that observed for WR+O systems (.4 is typical; see below), evolutionary models predict that the WR star has to be similar in luminosity (or less luminous) than the remaining O star, unless the initial mass ratio is quite high (Vanbeveren and Conti 1980).

Little spectral analysis has been preformed for the O star companions. Since the equivalent widths of the upper Balmer lines in single O star appears to be largely independent of subtype or luminosity class, their measured equivalent widths in WR+O systems directly yields the relative luminosity of the two stars (e.g., Massey 1980). Beyond this, it is difficult to judge even subtypes due to blending between He II λ 4542 absorption and emission. It is impossible to include a table of v sin i values for the companions and discuss the frequency of synchronous rotation; rotational velocities have seldom been measured. If appreciable mass transfer has taken place from the (now) WR star to the O star, then spectral anamolies might be present; more work is clearly needed here.

B. The Masses of WR Stars

For the SB2's, the orbit solutions reveal the minimum masses (m $\sin^3 i$) for each star, plus the mass ratio. For those systems which also eclipse, a lower limit can usually be placed on the orbital inclination i, which then yields a maximum value for the mass. Even the knowledge that an eclipse does not occur can be useful in placing a more stringent constraint on the lower limit for the mass of the WR star. The largest uncertainty in using the eclipse information is the lack of values for the radii of WR's. The normal assumptions present in light curve analysis which allow the radii to be solved for simply do not hold for these systems (e.g., Kron and Gordon 1950). Photometry exists for only 6 of the 14 SB2's. For the others, some approximate value for the inclination can be deduced only by adopting a mass of the companion appropriate to its spectral subtype.

Table 1 lists the masses for the known galactic SB2's, along with the minimum masses and adopted orbital inclination. For the systems with photometry I have chosen the inclination based on the light curve;

Table 1: Galactic WR+O

Star	Spectral Type	$m_{WR}\sin^3 i$	$\frac{m_{WR}}{m_O}$	Estimated i	Basis for i	m_{WR} ($M_\odot$)	Ref.
HDE 320102	WN3+O7	1.8	0.33	30°	m_O = 35	11	1
HD 90657	WN4+O4-6	8-11	0.52	50°	eclipse	18	2
HD 94546	WN4+O	8	0.34	...	none	$\geq$8	3
HD 186943	WN4+O9V	9-11	0.52	70°	m_O = 25	13	4
HD 190918	WN4.5+O9I	0.7	0.26	25°	m_O = 35	9	5
V444 Cyg	WN5+O6	9.3	0.40	78°	eclipse	10	6,7
				55°	m_O = 45	17	
CX Cep	WN5+O8V	5	0.43	$\geq$50°	eclipse	5-11	8
HDE 311843	WN6+O5V	40	0.84	70°	m_O = 60	50	9
GP Cep	WN6+O	...	>0.22	$\geq$50°	eclipse	10-25	4
CQ Cep	WN7+O	23	1.19	$\geq$40°	eclipse	>23	3
HD 97152	WC7+O7V	3.6	0.59	35°	m_O = 35	20	10
HD 152270	WC7+O5	1.8	0.36	25°	m_O = 60	20	11
γ Vel	WC8+O9I	17	0.54	$\leq$70°	no eclipse	>21	12
				~70°	m_O = 35	20	
CV Ser	WC8+O8V	11	0.48	70°	m_O = 25	13	13

References: (1) Niemela (this symposium); (2) Niemela and Moffat (1981); (3) Niemela (1980), (4) Massey (1981a); (5) Fraquelli and Horn (1981); (6) Ganesh, Bappu and Natarajan (1967); (7) Munch (1950); (8) Massey and Conti (1981); (9) Niemela, Conti and Massey (1981); (10) Davis, Moffat and Niemela (1980); (11) Seggewiss (1974); (12) Niemela and Sahade (1980); (13) Massey and Niemela (1981).

otherwise, masses were assigned to the O companion based on evolutionary tracks in the manner prescribed by Massey (1981b). Clearly these values should be viewed with a degree of skepticism. It is amusing to note that the WR star V444 Cygni has a mass near 10 only by adopting the inclination (78°) found by the analysis of Kron and Gordon (1950). With this inclination the mass of the O6 companion comes out rather low (25 M_O) for that expected for its subtype (45 M_O). A value for _i_ near 55° as suggested by this mass, leads to a mass of 17 M_O for this traditionally 10 M_O WR star. Admitedly there are uncertainties in deducing inclinations by assigning masses to the O companions on the basis of spectral types; nevertheless, one should recall the eclipse history of CV Ser (e.g., Schild and Liller 1975) before taking any light curve analysis too seriously either.

A table giving the mass functions for the SB1's is given in Massey (1981b) and will not be repeated here. By adopting any two of the three parameters m_O, m_{WR} and _i_, the third can be found. The masses of the O companions of Θ Mus, HD 92740 and HD 193428 are all normal for reasonable inclinations. The WN7 single-lined system MR 13 (Niemela, this symposium) has an unremarkable mass function f(m) = 5.5; if m_{WR} = 15 M_O, then m_O = 18 M_O, 23 M_O, or 92 M_O for inclinations of 90°, 60° and 25.°8, respectively.

The most striking thing about the masses listed in table 1 is their large range. The smallest upper limit that can be placed upon the mass of any WR star is 11 M_O for the WN5 member of CX Cep. The largest lower limit on the mass of any WR star is 40 M_O for the WN6 member of HDE 311843. It is impossible to significantly drive the former up, or the latter down, and one is forced to conclude that _the masses of WR star span a very large range_. This can be shown statistically with no reference to the adopted orbital inclinations: Smith (1968) demonstrated that the minimum masses of WR stars were strongly correlated with the mass ratios, in the sense that stars with smaller minimum masses were found in systems with smaller m_{WR}/m_O values. Since the minimum masses contain a $\sin^3 i$ term, while the m_{WR}/m_O values do not depend upon _i_, she speculated that possibly some systematic error was present in the mass ratios, which somehow depended upon viewing angle (Figure 1). Massey (1981b) showed that while the minimum

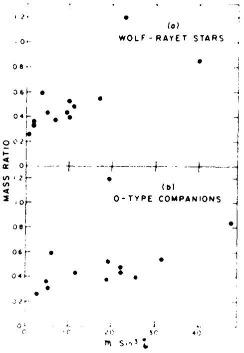

Figure 1. The mass ratios of WR+O binaries are strongly correlated with the minimum masses of the WR star, but not with the minimum masses of the O star companions.

masses of the WR stars correlated with mass ratio, the minimum masses of the O stars in the same systems are not. Therefore the correlation merely serves to demonstrate that the actual masses of WR stars must span a larger relative range than do their O-type companions.

The stars are arranged in table 1 by WR spectral subtype, to better reveal any systematic trends in the masses (or mass ratios). One finds instead that there appears to be little connection, if any, between subtype and mass. Two WR stars of similar subtype can lie at opposite extremes in the masses (e.g., the WN6 member of HDE 311843 and the WN5 member of CX Cep); stars of identical subtype can have quite different mass ratios (HD 90657 and HD 94546; HD 97152 and HD 152270). Two years ago this was a surprising find. However, during this symposium Leep has discussed the fact that stars of the same subtype can show large differences in their equivalent widths; Perry and Conti have demonstrated that not all stars of the same subtype have the same hydrogen to helium ratio (see also Conti and Massey 1980); Conti has emphasized the scatter that seems to exist in the absolute luminosity for WR stars of any subclass, and I have argued that the intrinsic colors of all WR stars of a given subtype cannot be the same. These conclusions all reinforce the interpretation that the subclasses define only some grossly averaged excitation temperature in the envelope.

Moffat (1981) has recently suggested that the mass ratios of WR binaries are correlated with subtype. His correlation is based primarily on the high mass ratio present for CQ Cep (WN7) and HDE 311884 (WN6), and the low mass ratio he finds for several WN3 binaries in the LMC with preliminary orbits. The work on WR binaries in the Magellanic Clouds is highly important, but may serve only to show differences in massive star evolution in different environments. The interested reader is invited to examine the numbers in table 1 and decide for him or herself whether any correlation exists for the galactic WR+O systems.

Another interesting fact that the table reveals is that the WC stars are not, in general, less massive than the WN stars. Either not all WN stars become WC stars, or else low mass WC stars are shorter lived than their massive counterparts. (Massey and Niemela 1981).

One other worthwhile exercise is to deduce the minimum fraction of its mass that an O star must lose in order to be identified as a WR star. By back-tracking the current masses of the O-type companions to their zero-age main sequence values, one can place a lower limit on the initial mass of the WR star. This can be safely done for the system containing middle or late O main-sequence stars, as these will not have lost a significant amount of their mass, and so their current masses must be nearly those of their initial values. These systems all have mass ratios less than 0.6. Since the initial mass ratio must have been greater than unity (since the more massive star evolves into the WR star), this implies that the WR stars in binaries have lost at least 40% of their initial mass.

C. Comparison with O+O Systems

In the Conti scenario (Conti 1976), a single O star will turn into a single WR star by stellar wind loss, while a binary O star (O+O) will turn into a binary WR star (WR+O) by wind loss possibly aided by Roche lobe overflow. Unanswered questions included (a) What relative importance do the two mechanisms have? and (b) What fraction of mass is accreted by the companion?

By comparing some of the observed properties of WR+O binaries with their evolutionary predecessors, we have hopes of answering some of these questions.

Figure 2 is a slightly updated version of Figure 2 in Massey (1981b), which shows the periods and mass ratios Q for O+O and WR+O systems. With the assumption that the WR star is originally the more massive member of the system, Q is defined as $m_{primary}/m_{secondary}$ for the O+O binaries, and m_{WR}/m_{O} for the WR+O systems. As the stars in an O+O system evolves, the initially more massive star will lose mass at a higher rate, and the star will move to the left in the figure.

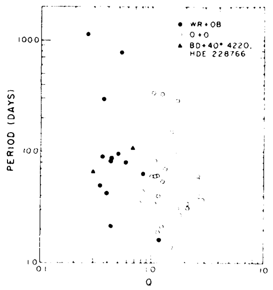

Figure 2. As an O+O star binary evolves, it moves to the left in this figure

One would like to use the observed distribution of periods as a function of Q to place constraints on the amount of mass transfer versus mass loss from the system. Unfortunately, it doesn't work. If all the mass is simply transferred, then both angular momentum and total mass will be conserved (under the most simple-minded picture); the laws of Newton and Kepler then demand a period increase by a factor of 2 in order for Q to change from 1.2 to 0.4 (see equation 3 in Massey 1981b). If instead mass is lost from the system we must somehow decide how much angular momentum is carried away: a decrease in total mass will lengthen the period; however, the decrease of angular momentum (carried away with the mass) will tend to lengthen the period. For spherically symmetric mass loss, the latter term wins, and we find that the period should increase by factors of 5 or so. However, it looks from figure 2 as if the period change is nil. For mass loss more angular momentum must be lost than can be accounted for by spherically symmetrical models.

Possibly the most instructive comparison that can be made between the O+O and WR+O systems is also the simplest: that of the total minimum masses. As long as the orbital inclinations of both types of systems are randomly distributed, then, on the average, one can directly compare the total minimum masses $(m_1 + m_2)\sin^3 i$ for both sets. The average $(m_O + m_O)\sin^3 i$ for all the double-lined O-type binaries is 33 $M_\odot$, using the values in table 3 of Garmany, Conti and Massey (1980). The average for all known WR+O binaries is 30 $M_\odot$ - nearly identical. Thus either evolution from O+O to WR+O systems is completely conservative, or WR stars are descended only from the more massive O stars.

Finally, it is useful to compare the orbital eccentricities of the two types of systems. The eccentricities of O stars can be found from the references in Garmany et al. All the W-R stars with massive companions have circular orbits except for γ Vel (e = 0.40), HD 190918 e = 0.43) and HD 92740 (e ∿ 0.6). These also happen to be the three with the longest periods (cf tables 1 and 2 in Massey 1981b). The longest period WR+O system with a circular orbit is CV Ser (P ∿ 30 days). Most of the O stars with periods below 30 days have circular orbits; all the long period systems have non-circular orbits. For the short period systems tidal interactions will circularize an orbit; however, if mass transfer has played a dominant role we might expect for the longer period systems to have circular orbits as well, since this is a consequence of mass transfer (e.g. Paczynski 1971; Piotrowski 1965).

III. WR + WR BINARIES

Besides the WR+O systems, one might expect one other type of WR binary with a massive companion: one in which the companion is another WR star. To produce such a system the O star in a WR+O system must evolve into a WR during the lifetime of the other WR star. Since the lifetime of a WR star is typically taken to be 10% of its O star life, one might expect one or two systems to be known. How would we identify such a system? The most obvious candidates are those which do not readily fit into the classification scheme; i.e., WR stars whose spectra show lines typical of more than one type. A perusal of the Sixth Catalogue (van der Hucht et al. 1981) reveals a number of stars classified as WN+WC - stars which show lines typical of both WN and WC stars.

I have spent the last year observing one of these stars, MR 111, from DAO with our cassegrain image tube spectrograph. MR 111 was announced to be a binary by Pesch, Hiltner and Brandt (1960), who demonstrated that He II λ 4686 showed velocity variations of about 400 km/sec with a (possible) period of 22 days. The spectrum is typical of a late WN star star, except that the strongest line present in the spectrum is C IV λ 5812. The lack of C III λ 5696 suggests this might be a WNL+WC4 binary. The obvious key to its nature lay in whether or not C IV moves in phase or out of phase with He II. The answer is that it moves in phase. This, at least, is not a WR+WR system.

Niemela (this symposium) discussed HD 62910, another suspected WN+WC binary. Although her data shows that the He I $\lambda 3888$ absorption edge has a variable velocity, no strong evidence is visible for velocity variations in either the N or C lines.

IV. SUMMARY

The following points are what I feel are the main clues provided us by the WR stars with massive companions:

(1) The masses of WR stars span a much larger relative range than do their O-type companions. There is little, if any, correlation between the masses (or mass ratios) and the spectral subtype of the WR star. The average mass of a WR star is about 20 $M_{\odot}$, but there is no one typical number.

(2) The masses of WC stars are not less than those of WN stars.

(3) WR stars in binaries have lost at least 40% of their mass in becoming WR stars.

(4) The periods of WR+O systems are similar to those of O+O systems. The mass ratios are considerably different, suggesting that more angular momentum must be lost for a given amount of mass loss than can be accounted for by spherically symmetric outflow.

(5) The average value of the combined minimum masses is the same for WR+O systems as for O+O systems. Either evolution from O+O systems is completely conservative, or only the most massive O stars become Wolf-Rayets.

(6) The long period WR+O systems all have non-circular orbits; all the short period systems have circular orbits, identical to what is known for the O-type stars. Mass transfer may not, therefore, have played an important role in the formation of WR+O systems.

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DISCUSSION

Doom: Could you give an estimate of what fraction of the WR stars with absorption lines are really WR stars with OB companions ?

Massey: Of the 13 WR stars with absorption lines present observable from KPNO and brighter than 12th magnitude, all have detailed high dispersion radial velocity studies. Seven of them are binaries, but the absorption is due to the companion in only 5 cases. But to be generous, let's say 60%. Since Vanbeveren and Conti found that only one third of all known galactic WR stars have absorption present, and since absorption lines must show up in the spectrum of a WR+O system (unless the WR star is a WN7), the overall incidence of WR+O systems must be less than about 20% (Massey, Conti and Niemela, Ap.J., 246, 145).

Underhill: I must emphasize once again that no spectroscopic reasons have been given that the spectra of any stars change from type O to type WN to type WC as the star evolves. The emission lines of Of and WR spectra are created by conditions in the superficial layers of the atmosphere. It has not been demonstrated that the creation of these conditions follows automatically as a massive star evolves with mass loss and that conditions suitable for generating first Of, then WN and finally WC spectra occur in the assumed order.

Massey: I know of no B star with a mass of $45M_\odot$. Furthermore, Katy Garmany has noted that there are few, if any, O-type binary systems with large mass ratios. So if the WR star in an O+WR binary didn't come from a high mass object, it's a little hard to see where it did come from.

Smith,L.F.: I do not think it is yet time to disregard the generalisation that the separation of WC binaries is greater than the separation of WN binaries. If you calculate those separations, using the data in your table, including your estimate of the inclination, the separation of all WC binaries is greater than $80R_\odot$ and the separation of all but one of the WN binaries is less than this limit.

Massey: When you made the suggestion at the 1971 Beunos Aires Conference, there were four WC+O binaries known, 3 with long periods and hence large separations, and 1 with a short period (HD 152770). Subsequently one of these "long period systems " (HD 193793) was found to be single (Conti, Roussel-Dupree, in preparation). One new orbit solution for a WC has been done, namely HD 97152 by Davis et al. (Ap.J. 244, 528). That one has a short period. So we are still dealing with n=4 statistics, only now two of them have relatively small separations and two have large ones. If you do plug in my inclinations to the a sin i values I do not think the evidence is overwhelming for a difference between the two types. Certainly there are WN systems with large separations and WC systems with modest separations. However, it's hard to do a meaningful histogram for 4 objects.

Breysacher: Concerning the relation between eccentricity and period of WR binaries, could you give some values ?

Massey: As I recall, all the WR binaries with $P > 30$ days have non-zero eccentricities (e.g. γ Vel, HD 190918), while all those with $P < 30$ days have nearly zero eccentricities. There is a list in Massey, (Ap.J., 246, 153, 1981).

Hiltner: Would you be so kind as to elaborate on the determination of the rather large mass for CQ Cephei ?

Massey: Niemela (IAU Symp. 88, p 177) has a double-lined orbit solution for this system which suggests a mass ratio of 1.2 and a minimum mass of the WN7 of $23M_\odot$. She also found that most of the absorption lines move in phase with the emission. I believe that in a later paper Moffat and collaborators confirmed her result, although I haven't seen the paper yet.

Moffat: Our observations of CQ Cep indicated that the nearly central absorption lines (e.g. H9) move in phase with the best emission lines. Also Lenny's analysis of Hiltner's light curve yields $i \sim 78^\circ$ (Lenny, Moffat and Seggewiss, 1982, submitted to Ap.J.).