EVOLUTION OF MASSIVE STARS: WHEN DOES AN Of STAR BECOME A WR STAR?

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ABSTRACT

Detailed spectroscopic work has begun for several stars that have been classified WN 7. All show absorption lines in the upper Balmer series and in ionized helium. The absolute magnitudes, established from cluster membership, are relatively brighter than those of most other WR stars. In this paper the outflow velocity near the stellar photosphere is shown to be similar to that in Of stars. These WN 7 stars show somewhat larger emission line widths and probably have less hydrogen in their envelopes, but otherwise have similar luminosities and temperatures as Of stars.

The overall properties of WR stars are well known (e.g., Smith 1973). The stars are hydrogen poor, helium rich, and characterized by strong emission lines which dominate the optical spectrum. The two classes, WN and WC, are thought to be chemically distinct stars in which the products of hydrogen burning CNO reactions (WN) or helium burning (WC) are brought to the surface (Paczynski 1973). In principle, WR objects can be produced by stripping away the hydrogen rich layers of massive stars, either by mass exchange in a binary (Paczynski 1973), or by winds from single or binary stars (Conti 1976). Of stars are those O-type objects in which the stellar wind is sufficiently strong that op-

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tical emission lines are seen (Conti and Leep 1974). The observed mass loss rates range from 10^{-5} to $10^{-6} M_{\odot} yr^{-1}$ (Snow and Morton 1976; Conti and Frost 1977). A mass loss rate of a few times $10^{-6} M_{\odot} yr^{-1}$ is sufficient to considerably alter the evolution of the star while it is still burning hydrogen in the core, and subsequently, as discussed independently by Chiosi _et al._ (1977) and de Loore _et al_. (1977). In particular, the general lack of later type supergiants, compared to blue supergiants, can be understood in terms of substantial mass losses in the previous evolutionary phases.

There is a distinct set of WN stars that, unlike most WR stars, contain appreciable amounts of hydrogen. These stars have been called "transition" objects (Conti 1976) because of their spectroscopic similarities to Of stars. Their emission line widths and strengths are less than those of most other WR stars. In some cases absorption lines in the upper Balmer series are observed (Niemela 1973). Although the term "transition WR" implies only spectroscopic similarities to Of stars, it may also have an evolutionary connotation: The transition stars may be descendant _from_ Of stars and evolving _to_ WR stars. Chiosi _et al_. (1977) and de Loore _et al_. (1977) are able to place these "transition" stars in an evolutionary sequence descendant _from_ massive Of stars with sufficiently high mass loss rates. For the former authors, the stars are burning helium in their cores; for the latter, hydrogen core burning still operates. The location of these objects in the theoretical HR diagram is, however, similar in both cases.

The mass loss rate of a star is established by the envelope. The most important parameters are the velocity gradient and its terminal value, and the wind density. The extent, composition, and radiative temperature are important but only indirectly affect the determination of the mass loss rate. It appears likely that most spectroscopic differences between O, Of and WR stars can be completely accounted for by variations of these envelope parameters. Any other physical differences between Of and WR stars may then be differences of interior structure, hydrogen or helium burning, and stellar mass.

Three "transition" WN stars and the related object HD93129, type O3f, will be discussed briefly here. This work is part of a more detailed study of these stars (Conti, Niemela and Walborn 1978). The WN stars, HD 92740, HD 93131, HD 93162 and HD 93129 are members of the Carina association (Walborn 1973) and have relatively bright M_V, between $-6\overset{m}{.}5$ and $-7\overset{m}{.}0$. HD 92740 appears to be a single line spectroscopic binary (Niemela 1973) with emission and absorption lines in phase. The period has now been firmly established at about 80 days (Conti, Niemela and Walborn 1978). Although the mass function is 1.83, the secondary has not been detected as yet.

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The star HD 93131 shows no evidence for periodic variable radial velocity. The star HD 93162 shows some scatter in radial velocity but at the writing of this paper all the data have not yet been reduced. HD 93129 shows no significant velocity variation. For these three stars, then, it is possible to assume for the present they are single and average velocities for all lines measured. The results are plotted in Fig. 1. The velocity of the Carina association has not been firmly established but the few single O-star members measured so far by Conti, Leep and Lorre (1977) have velocities in the range -5 to -20 km s^{-1}.

It can be seen from Fig. 1 that the absorption and emission line velocities of HD 93129, the O3f star, are slightly negatively displaced with respect to the association. There is no convincing "Balmer progression" up to Hγ. Hβ is weak on the plates used and both it and Hα, which is in emission, are distorted by nebular emission. HD 93162 and HD 93131 have a very strong Balmer progression and all absorption lines are violet displaced with respect to the (narrow) emission lines of N III, N IV (4057 Å only), and Si IV. These emission lines are at roughly the same velocity as those in HD 93129. The Balmer progression is stronger in HD 93131 than in HD 93162, which is also the ordering of emission line strengths.

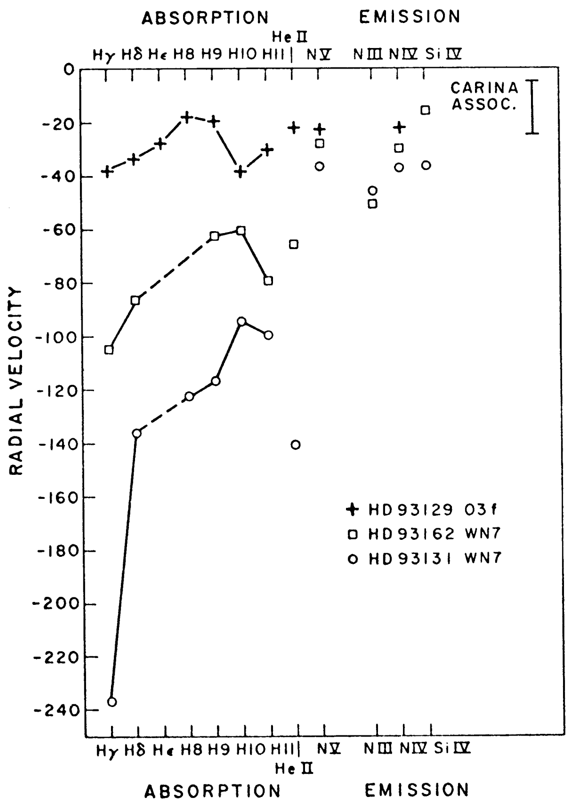

Fig. 1. Absorption and emission lines as indicated for two WN7 stars and HD 93129. There is no emission associated with the upper Balmer lines but in the two WN7 stars emission begins to appear at about Hϵ and lower in the series. By Hγ emission dominates the line profile. There is evidence of a strong Balmer progression (increasing outward velocity with decreasing quantum number) in the two WN stars. There is little or no progression in HD 93129. The emission and N V absorption velocities in all three stars are close to that of the Carina association. This figure gives a quantitative estimate of the beginnings of the outflow of the envelope in the three stars.

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Under the usual assumption that velocity increases outwards, it must be that the narrow emission lines are formed in a level similar to, or lower than, that of the Balmer absorption lines. The N V absorption lines, of high excitation and ionization, are also formed at this low level. Balmer progressions have been found previously in Of stars (Hutchings 1968; Conti, Garmany and Hutchings 1977; Leep 1978), and tentatively by Niemela (1977) for two of these WN stars. A line-by-line comparison of the actual radial velocities shows at least some Of stars have outflow velocities intermediate between those in HD 93162 and HD 93131.

The broad emission lines, such as 4686 Å He II, 3478, 3483 Å N IV and 4603, 4618 Å N V, are shifted redwards of the other emission lines in this figure. This suggests they are formed in a relatively large extended region around each star; the net red shift is then a result of scattering in an expanding envelope -- the so-called Auer-van Blerkom effect (Mihalas 1974). This effect is well known in double-lined WR binaries where the gamma velocities of the broad emission from the WR star and the absorption lines from the O star frequently differ. An analogous effect is also seen in certain Of stars (Bohannan and Conti 1976; Massey and Conti 1977).

A further inference from Fig. 1 is that the presence of absorption lines in a WR star is no guarantee that the star is double. Statements of WR duplicity including such stars may well overestimate the actual fraction. Very preliminary results on emission line widths by Leep (1978) show that the lines in even these WN stars are somewhat wider than those strongest lined Of objects. The wind densities are probably different, even though the velocity gradients may be similar in some cases. It appears that the H/He ratio is different between Of and these WN stars. The normal ratio of 10 may not be true for all Of stars (e.g., Conti and Frost 1977) but probably no Of star has a value as low as 2 as found by Smith (1973) for several other late-type WN stars. An abundance analysis of these transition objects is currently under way.

Masses unfortunately cannot be derived for stars showing no velocity variations and even single lined binary systems such as HD 92740 can add little to our knowledge. From evolutionary tracks of Chiosi et al. (1977) and de Loore et al. (1977) it appears likely that transition stars will be relatively massive objects of about 40 solar masses. These values certainly overlap those of Of stars. The transition WN stars occupy the same region of the HR diagram as Of stars.

The remaining physical distinction between Of and these transition stars may be one of H/He ratio and interior structure. If the Of stars are burning hydrogen in the core, and the transition

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and WR stars helium in the core, the differences might be understood.

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DISCUSSION

PARTHASARATHY: Spectral lines of the secondary components in some of these systems are seen only at certain phases and also show variations in intensity with orbital phase. Radial velocities of the secondary component obtained from these lines may not represent the true orbital motion.

CONTI: I don't think this is now the case for any of these Of systems. There is a new orbit of Plaskett's star by Cowley and Hutchings (Astrophys. J. 1977) and I think their evidence about the secondary is reasonably compelling. Dr. Nancy Morrison of JILA has many high dispersion spectrograms of HD 47129 and 29CMa and is presently studying them. The secondaries are visible.

BIDELMAN: What is your explanation for the WC stars?

CONTI: It could be either of the following ways to bring the products of helium burning to the surface: (1) evolution from a WN star, sufficient mass loss occurs only after an O star has commenced helium burning; or (2) perhaps only OC stars can become WC stars directly: the carbon anomaly then would already exist.

COX: How is it that we know that the Wolf-Rayet stars are helium burning?

CONTI: There are two arguments, as outlined by Paczynski at IAU Symposium #49: (1) The WR stars generally do not show evidence of hydrogen in their spectra; helium dominates. Since little or no hydrogen remains, hydrogen burning is not possible. (2) The luminosity, compared to the mass, is consistent with that for pure helium stars burning helium in their cores.

PISMIS: Are there sufficient data to know whether there are differences in the kinematic characteristics of the spectral groups you discussed as well as the distribution in the Galaxy, I mean for the groups of normal O, Of and WR stars?

CONTI: All stars belong to the extreme Pop. I in terms of their kinematic properties. There is an absence of WR stars towards the galactic anti-center. probably a result of fewer O stars being present. There are, of course, some nuclei of planetary nebulae with spectra which are Of or WR type. These phenomena are therefore not restricted to Pop. I objects.

PARTHASARATHY: What are the reasons for the under-luminosity of the massive secondary components in systems like HD 47129, UWCMa and others?

CONTI: I don't really have a detailed answer for this. For close binaries such as these we will undoubtedly have to consider mass loss from the system, along with mass exchange, as affecting the stellar evolution. I would think a very non-equilibrium situation exists for the stellar structure configurations.