SOME PROGRESS AND PROBLEMS IN THE UPPER LEFT OF THE HR DIAGRAM

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1. AN EMPIRICAL LUMINOSITY CLASSIFICATION FOR EARLY O STARS

The MK system of spectral classification does not include luminosity classes for types earlier than O9. Subsequent work with higher dispersions has allowed a luminosity classification for early O stars to be proposed. One of the principal criteria at types O9-B0 is the selective, negative luminosity effect in the HeII 4686 Å absorption line; a similar effect was found in the NIII 4634-4640-4642 Å absorption lines at O9-B0. These particular lines weaken markedly with increasing luminosity, while other HeII lines maintain a constant ratio to HeI (by definition), and other NIII lines strengthen considerably. These anomalous lines are the same ones which selectively appear in emission in Of stars, and the derived luminosity classification for earlier types is based upon the hypothesis that the negative absorption effect at O9-B0 is due to emission filling by the same mechanism producing the Of phenomenon, and that hence the latter may also be identified as a luminosity effect (Walborn 1971). One observes strong 4686 Å absorption and often weak 4640 Å emission [denoted ((f))] on the main sequence to the earliest types. As luminosity increases at a given spectral type, the HeII absorption weakens while the NIII emission increases [denoted (f)] and finally the most luminous stars have both 4686 and 4640 Å strongly in emission [denoted f]. A sequence of spectra all with types very near O7, but showing the marked changes with luminosity class in 4686 and 4640 Å, is illustrated by Walborn (1973). These effects show good agreement with other spectroscopic luminosity criteria

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such as SiIV absorption (Conti and Alschuler 1971) and Balmer-line strength (Crawford 1975, Morrison 1975), which are however less sensitive at the earliest types.

The absolute visual magnitudes of O stars with independently known distances support the empirical luminosity classification. The Of stars have M_V's near $-7^m.0$ to the earliest types, while the hottest main sequence stars average $-5^m.5$ (Conti and Alschuler 1971; Walborn 1972, 1973). Further calibration information is desirable, however, and provides one motivation for observations of O stars in the Magellanic Clouds. Theoretical support for the luminosity classification is provided by the work of Mihalas et al. (1972) and Mihalas and Hummer (1973), who have reproduced the observed behavior of the NIII lines as a function of temperature and gravity. These results provide a good demonstration of the value of detailed morphological investigation; previously spectra in all three of the above-mentioned categories had sometimes been classified "Of", and when absolute-magnitude differences from pure absorption-line O stars were sought, of course no clear conclusions could be reached.

Following the resolution of some initial divergences, there is now excellent general agreement between this morphological work and the extensive, parallel studies of O-type spectra at coudé dispersions by P.S. Conti and collaborators (Conti and Leep 1974). The value of morphology is that it enables one to perceive more readily the forest (and its substructures) among the trees, while the quantitative approach provides the essential data for comparison with physical theory (Conti 1973a, b; Conti and Burnichon 1975).

In summary, I think the Of stars may now be removed from the category of "peculiar stars" where they are often found. They are simply the early O-type supergiants, and their spectra represent the behavior of stellar atmospheres and certain atomic species at the relevant temperatures and gravities (although complete physical interpretations await more detailed, future theoretical models). However, while refined morphology may remove some classes of stars from the peculiar category, it invariably reveals at the same time more subtle kinds of peculiarity, to some examples of which I'll now turn.

2. EXTENDED-ENVELOPE PHENOMENA

2.1 Onfp Stars

The principal peculiarity is a combined emission/absorption structure in HeII 4686 Å, which could be described as an absorption with emission wings, or as a centrally reversed emission (Walborn 1972, 1973). As implied by the notation, these stars invariably have broadened absorption lines suggestive of

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rapid rotation. This category has been denoted Oef by Conti and Leep (1974), who inferred a relationship to the Be phenomenon.

2.2 Of?p Stars

The defining characteristic is CIII 4647-4650-4651 Å emission comparable in strength to NIII 4634-4640-4642 Å (Walborn 1972, 1973, and references therein). Only 3 stars (HD 108, 148937, 191612) have been so classified to date. The emission features appear excessively sharp relative to the stellar absorption lines, and there are other suggestions of a shell phenomenon rather than an extension of the stellar atmosphere as in normal Of stars. The interrogative in the notation is intended to express doubt that these are normal O-type supergiants. There is evidence that they are massive, Population I objects, although the CIII emission property is shared by some Of-type nuclei of planetary nebulae (Heap 1977, Thackeray 1977). HD 148937 is associated with expanding nebulosity apparently ejected from the star (Catchpole and Feast 1970, Pismis 1974). Binary motion has been reported for HD 108 by Hutchings (1975), while Conti et al. (1977) did not find variable velocity for HD 148937.

2.3 OIafpe Stars

The pre-eminent peculiarity is a pronounced P Cygni spectrum. These stars are definitely highly luminous supergiants. Conti et al. (1977) concluded that the well-known example HD 152408 in Scorpius OB1 is not a spectroscopic binary. Two objects recently observed in the Large Magellanic Cloud (HDE 269858 and Sanduleak -67° 266) show probable evidence of extreme envelope extent; the SiIV 4089 and NIII 4097 Å absorption lines have interstellar-like profiles at moderate resolution (Walborn 1977).

2.4 WN Stars

The necessary characteristic which distinguishes these spectra from any of the previously discussed categories is the presence of broad emission bands. Two basic questions which must be answered are (i) whether or not these objects occur only in binary systems; and (ii) what is the relationship between the high-luminosity, narrow-line WN-A stars, usually found in massive young regions such as 30 Doradus, the Carina Nebula, and Scorpius OB1, and their lower-luminosity, moderate-mass counterparts such as V444 Cygni. The Of binaries VI Cygni No. 5 and HDE 228766 may be pre-WR systems (Bohannan and Conti 1976, Massey and Conti 1977). There are clear morphological relationships

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between O3-4f and WN-A spectra (Walborn 1974). However, it is essential to determine which objects are binaries and which are probably single stars, before possible evolutionary relationships can be inferred with any confidence. The O3f star HD 93129A and the WN-A stars in the Carina Nebula are currently the subjects of a radial-velocity study by P.S. Conti, V.S. Niemela and the writer.

3. CHEMICAL ANOMALIES

3.1 OBN/OBC Stars

The observational details have recently been reviewed (Walborn 1976) and need not be repeated here. Bolton and Rogers (1977) have found that many and possibly all OBN stars are spectroscopic binaries, while none of the OBC stars are members of short-period binaries. The OBN phenomena may represent relatively extreme nitrogen enrichment due to mass transfer in binary systems, while the most significant aspect of OBC spectra may be their nitrogen deficiency. The systematic, relative nitrogen deficiency among late-O and early-B supergiants in the Orion Belt and NGC 6231 (Scorpius OB1) could be interpreted as evidence that all OB supergiant atmospheres undergo evolutionary nitrogen enhancement to some degree during their lifetimes as such. A very important result was obtained by Baschek et al. (1972), who found that the spectroscopic differences between ζOri (Orion Belt) and HD 188209 (morphologically normal CNO spectrum) could be explained by an admixture of 20 to 40% CNO cycle-processed material in the atmosphere of the latter star. Dearborn and Eggleton (1977) have suggested that mass loss could produce such an effect. If an evolutionary interpretation of these phenomena is substantiated, the fact that they are observable must be reconciled with the time scales for OB supergiants. It may be of interest in this connection that some recent models (Stothers 1976, Stothers and Chin 1977) imply more extended time scales for OB supergiants. Currently high-dispersion observations of many of these stars are being obtained by J.B. Lester, to provide data for quantitative analysis.

3.2 Helium-Rich Stars

This term refers to Population I, main-sequence objects near type B2V with enhanced HeI spectra (Osmer and Peterson 1974 and references therein). The bizarre, periodic Hα emission variations in the prototype object σOrionis E (Walborn and Hesser 1976) and its peculiar light and color curves (Hesser et al. 1977) suggest a binary interpretation, as do variable shell absorption features (Groote and Hunger 1977) and periodically variable linear polarization (Kemp and Herman 1977). However, no radial-velocity curve is observable to stringent limits, indicating a very low mass for

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any secondary, and an oblique-rotator model is preferred by Shore and Bolton (1977). See also Montmerle and Michaud (1976). It is fair to say that all the proposed interpretations of this puzzling object encounter some difficulties; further investigation is certainly indicated. Many of the He-rich stars have recently been found to have periodically variable He spectra (Bond and Levato 1976; Pedersen and Thomsen 1977).

3.3 Metal Deficiency in the SMC

There is a consensus among several recent spectroscopic studies of supergiants in the Small Magellanic Cloud, to the effect that they have systematically weaker metallic lines than their galactic counterparts. These studies have included types B2-3 (Osmer 1973), A (Przybylski 1972, Feast 1976), B0 (Walborn 1977), and a range of types (Dubois et al. 1977). The same phenomenon is seen in the spectrum of SMC X-1 (Sanduleak 160, Hutchings et al. 1977). The writer found that the SiIV/HeI line ratios in 2 SMC B0I spectra are similar to those in galactic stars of luminosity class IV, and some further examples have been observed during the current season. The first extremely early O star known in the SMC has also been found; it is difficult to judge metallicity in optical spectra of such hot stars, but it may well share the apparently general metal deficiency. These massive, metal-deficient stars may prove to be of considerable interest, not only for what they can tell us about the SMC, but also as representatives of a species now extinct in our Galaxy.

4. CONCLUSION

The extended-envelope and anomalous chemical phenomena discussed above are the most important puzzles presented by the spectra of the early-type stars at the present time. The questions, both explicit and implicit, are numerous. Why does one luminous, unstable object become a P Cygni star and another a WN star? The importance of information about the binary or single-star nature of each object has been emphasized throughout; before progress can be made, it is necessary to know which of these phenomena result from interactions in massive binary systems, and which are structural or evolutionary states of massive single stars. If very low-mass companions are involved, the issue may be extremely difficult to resolve. But even then, why does one interacting system become a WN and another an OBN binary - - or are they different phases of the same kind of object? The significance of these peculiar spectra should not be underestimated. Some may turn out to be mere curiosities, but others may provide keys to an improved understanding of massive stars, once the diffusion, mixing, mass-loss, mass-transfer, or other physical mechanisms at work can be correctly identified. Until these phenomena have been explained, the possibility cannot be excluded that some aspects of current interpretations of massive stars may change, even qualitatively. It seems clear that the upper left of the HR diagram will be an area of considerable research interest for some time to come.

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DISCUSSION

SREENIVASAN: If the Onfp stars are single objects, information about their (spin) rotational velocities is of considerable significance for their evolutionary picture. Do you have information about their v sin i? Also, the resolution of their single or binary nature is of great importance for producing proper evolutionary models including mass-loss and/or mass exchange. If v sin i is appreciable, centrifugal forces must be included in the mass-loss treatment. So, such observational guidance for modeling is crucial.

DR. WALBORN PASSED THE QUESTION TO DR. CONTI: Individual rotational velocities, v sin i, of a large number of O-type stars have been published by Conti and Ebbets (Ap. J. 1977). The Oe and Oef stars, the latter being our designation of "Onfp" stars, generally have relatively the largest v sin i among the entire set. This is similar to the situation for Be stars vis a vis normal B stars. A few Oe stars have relatively sharp lines, presumably as they are "pole-on". We believe that Oe and Oef stars are related to O stars as the Be stars are to B stars.

As far as duplicity is concerned, Dr. Katy Garmany of JILA is presently studying this question for about 10 Oe and Oef stars. A very preliminary remark is that there are no large velocity amplitudes among these stars.

WALBORN: Can you give a typical value of v sin i for the majority of them?

CONTI: Oh, I'd say they're between 150 and 200 km/sec.

NORRIS: Would you comment on the incidence of helium weakness in the B star range? In particular is it still true that no helium weak objects are found with temperatures greater than that corresponding to B2.

WALBORN: I have not worked on these stars myself, but to my knowledge the statement holds true.

APPENZELLER: Can you give us an estimate of the percentage of the O stars which show chemical anomalies?

WALBORN: The extreme OBN/OBC stars comprise no more than about 5% of all OB stars I've observed. However, one possible interpretation of the observations is that all late O-early B supergiants undergo atmospheric nitrogen enrichment. In that case the N-deficient spectra may actually show "normal" abundances (i.e., those determined from B main-sequence stars) while morphologically normal supergiant spectra may be nitrogen-enhanced.