A Massive Star Odyssey, from Main Sequence to Supernova
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The earliest O-type stars

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Abstract. High-quality, blue-violet digital spectroscopy has been assembled of most previously known (and one new) members of the O3 class that exhibit N IV emission and N V absorption lines, with the collaboration of most specialists in the field. A detailed comparative study has led to the introduction of new spectral types O2 and O3.5 to describe the range of classification criteria present. Primary reliance has been placed on the N IV/N III selective emission-line ratio, because of various difficulties affecting the interpretation of weak He I absorption lines in some of these spectra, which are discussed. Some representative spectra defining the new types are shown. The majority of the O2 - O3 class members reside in the LMC. Their large ranges of luminosities and masses suggest a close evolutionary connection to the WN class, as do several spectroscopic and spatial relationships. The salient characteristics of O2 - O3 spectra in the ultraviolet longward of 1200 Å have been established for some time by *IUE* and *HST* data. Recently, the rich 900–1200 Å range has been well covered for the first time by *FUSE*; in a collaboration with its hot-star team, a comprehensive atlas of OB spectra in the Magellanic Clouds has been prepared. Several O2 stars are included, one of which is newly discovered, and some examples of these data are also shown.

1. Introduction

Spectral type O3 was introduced 31 years ago to describe several stars in the Carina Nebula hotter than the earliest MK standards (Walborn 1971). The defining characteristic of the new type was the non-detection of He I λ4471 in the widened photographic spectrograms then in use, whereas it was a weak but well defined feature in O4 spectra. In addition, one of the Carina Nebula stars, HD 93129A (O3f*), presented a new kind of O-type spectrum, with a narrow N IV λ4058 emission line *stronger* than the normal Of N III $\lambda\lambda$4634-40-42 lines, which was denoted as Of*, and strong N V $\lambda\lambda$4604-20 absorption lines. These N IV and N V features are present in O4f spectra, but much more weakly and with the N IV weaker than N III . Thus, the emission-line (N IV/N III) and absorption-line (He II/He I) ratios were found to be correlated in these spectra. This behavior in modern digital data is well shown in Walborn & Howarth (2000).

Subsequent quantitative work has verified the extreme properties of the O3 stars in terms of effective temperatures, masses, and stellar winds (see references in Walborn *et al.* 2002a). Many new examples of the class have been discovered by various investigators. The work just cited contains a collection of blue-violet, digital spectroscopy for many of them, the study of which has led to a subdivision of the former O3 class into three new classes describing the range of classification criteria present, which is discussed in detail in that paper and will be summarized here. The correlative behavior of the ultraviolet stellar-wind profiles will also be reviewed.

2. New spectral types O2 and O3.5

2.1. Classification criteria

The original O3 class was bounded only on the low-temperature side, since by definition the horizontal classification criterion, the He ionization ratio, had disappeared. One might have hoped that with improved data quality, a range of weak He I line strengths would be detected, supporting some lifting of this degeneracy. However, that has turned out not to be the case, because of at least four issues affecting the interpretation of weak He I lines in the hottest spectra, that cannot be resolved by the classification material itself:

- the detection of weak absorption lines against the continuum noise is highly dependent on the resolution and signal-to-noise;
- strong He I lines in an O3 spectrum are a certain signature of a composite spectrum with a later-type companion, but weak He I lines in high-quality data may be either from a companion or intrinsic. Many or most of the most massive stars occur in multiple systems. Even with extensive radial-velocity monitoring and the highest resolution imaging techniques available, it may be impossible to eliminate this uncertainty;
- many of the hottest stars are found within inhomogeneous emission nebulae. Under- or over-subtraction of the nebular He I emission lines at moderate resolution can easily distort the stellar absorption-line intensities;
- some WNL spectra have He I wind profiles that are formed in the optically thick expanding envelopes. It is possible that some of the hottest O-type supergiants may have such features incipiently in their winds.

For these reasons, it has been found preferable to shift the primary horizontal classification criterion in the hottest O-type spectra to the N IV/N III emission-line ratio, which displays a large range in spectra previously classified as O3, and is not subject to the problems affecting the He I absorption lines. It should be emphasized that these are *selective* emission lines, *i.e.*, lines that come into emission while others from the same ions remain in absorption, and that display the same profiles as the absorption lines in a given spectrum as well as smooth temperature/luminosity dependences (Walborn 2001). The observed behavior of the N III Of lines has been reproduced as a function of temperature and gravity by Mihalas, Hummer & Conti (1972), in terms of special processes populating and depopulating the atomic levels under the relevant physical conditions. Thus, such lines may be expected to provide good classification and atmospheric diagnostics.

On the basis of the behavior of the N IV/N III emission-line criterion in the expanded sample of digital data, Walborn *et al.* (2002a) found that spectra previously classified as O3 are best described by three subclasses, including the new ones O2 and O3.5, defined so as to minimize revisions to the existing scales. The detailed criteria and standards at the dwarf, giant, and supergiant luminosity classes are presented and discussed in that paper. As an example, the supergiant spectral sequence is reproduced here in Figure 1.

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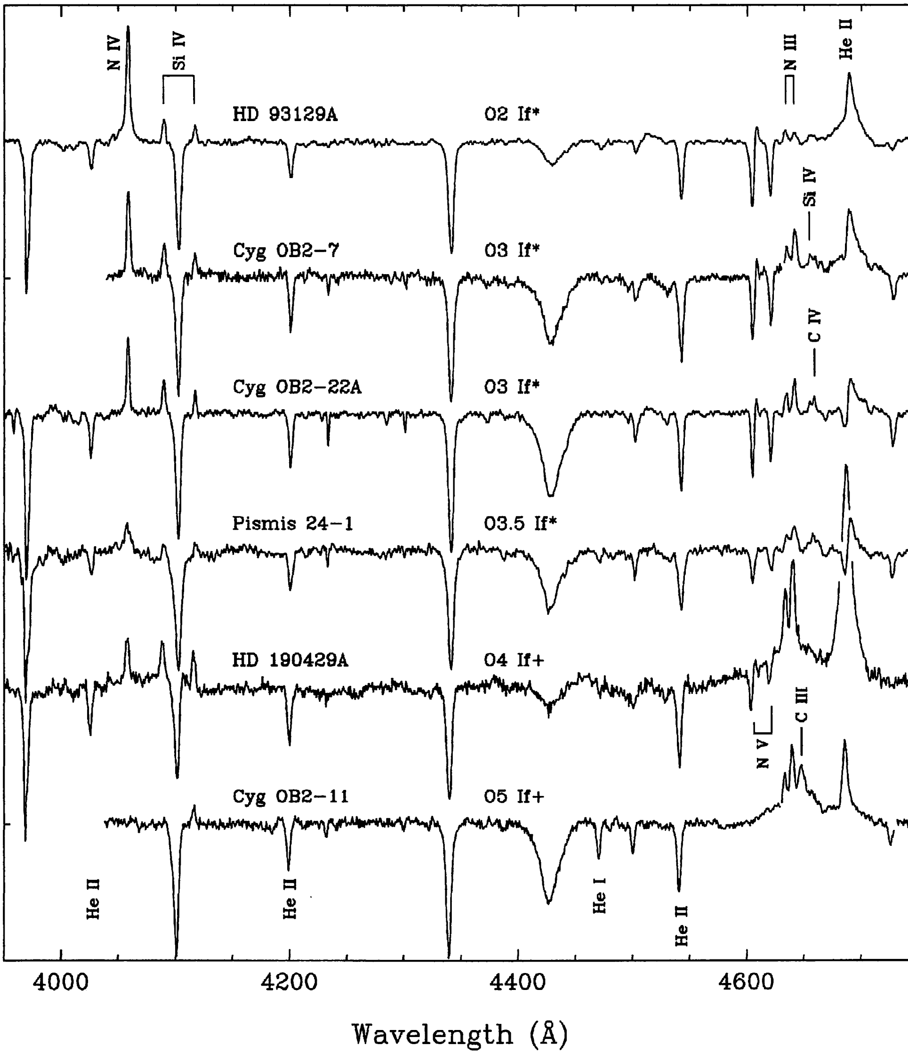

Figure 1. Sequence of the earliest O-type supergiant spectra, illustrating the newly defined O2 and O3.5 spectral types. The rectified spectrograms are separated by 0.3 continuum units. Kindly adapted by Ian Howarth from Walborn *et al.* (2002a) and Walborn & Howarth (2000), where further details can be found.

2.2. Census and locations

A total of 45 former O3 stars displaying the N IV and N V features, now reclassified as O2 through O3.5, are listed by Walborn *et al.* (2002a). Just two of them are located in the Northern Hemisphere, both in the Cygnus OB2 association, including the new member of the class Cyg OB2-22A, which is in a previously unresolved visual binary with a later O-type companion. Eight members of the class are located in the Southern Milky Way. One is in the Small Magellanic

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Cloud giant H II region NGC 346, while the remaining 34 belong to the Large Magellanic Cloud, with no fewer than 20 of the latter in or near 30 Doradus.

2.3. Absolute visual magnitudes and masses

The derived absolute visual magnitudes of the O2 - O3.5 stars display a surprisingly large range at a given luminosity class, considerably greater than what is found for most later O-types. There is a trend in the expected sense, but the individual values overlap among the luminosity classes. In the Galaxy, distance and reddening uncertainties contribute to this result, as do unresolved multiple systems in all three galaxies. However, it appears unlikely that these sources of error are the entire explanation of the observed scatter, which probably has a substantial intrinsic component. One reason for this conclusion is the peculiar behavior of the primary luminosity criterion He II λ4686, which develops incipient or full P-Cygni profiles in most of the O2 - O3.5 giants and supergiants, unlike at later O-types. The detailed spectral morphology at the earliest O-types may be significantly determined by the stellar winds and evolutionary states, in addition to luminosity.

Of course, the stellar masses derived from the luminosities of the O2 - O3.5 stars display an analogously large range, from about 50 to 200 $M_{\odot}$ according to one calibration and methodology. A possible interpretation of this result will be discussed in the next subsection.

Subsequently to the discussion by Walborn *et al.* (2002a), E. Nelan has observed HD 93129A with the *HST* Fine Guidance Sensor interferometer and resolved it into a 60 mas binary with a magnitude difference of 0.5 (preliminary numbers)! As mentioned above, this star was the prototype O3 If*, now O2 If* (Figure 1), and it has provided an anchor point in quantitative analyses of the most massive stars (*e.g.*, Taresch *et al.* 1997). The FGS result introduces even more scatter into the physical parameters of the hottest Population I stars. A similar result has been obtained for HDE 303308, another of the hottest stars in the Carina Nebula. These results for some 'well known', relatively nearby stars emphasize anew the fundamental uncertainties introduced by the endemic multiplicity of the O-type stars, frequently at or beyond the detection capabilities of current techniques.

2.4. Immediate WN progenitors

Close spectroscopic and spatial relationships between O3 and WN stars have been clear since the outset: there are three late WN-A, or WNL, stars in the Carina Nebula with similar luminosities and strong spectroscopic affinities to HD 93129A (Walborn 1974). Similar cohabitation was found in 30 Doradus (*e.g.*, Massey & Hunter 1998 and references therein) and the Galactic giant H II region NGC 3603 (Drissen *et al.* 1995). The large N/C ratio in the wind of NGC 346 No. 3 is particularly striking (Walborn *et al.* 1995, 2000; Haser *et al.* 1998) and may well be representative of all O2 - O3 stars, although it is more difficult to detect than in the SMC because of saturation in the C IV profiles.

There are large ranges in the luminosities and masses of WNL stars, which are likely related to their different formation channels: very massive single stars in giant H II regions, post-red supergiants at lower masses, and mass-transfer binaries down to still lower masses. If all of these diverse WNL phenomena

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are immediately preceded by a hot O2 - O3 stage, then a comparable range of luminosities and masses within the latter would be expected.

3. Ultraviolet spectra

3.1. *IUE* and *HST*

For some time there has been good coverage of the ultraviolet spectra of the O-type stars down to about 1200 Å, with moderately high resolution and extensive samples. The Galactic stars were well covered by the *International Ultraviolet Explorer* (*e.g.*, Walborn, Nichols-Bohlin & Panek 1985; Snow *et al.* 1994), while the spectrographs on the *Hubble Space Telescope* have extended the coverage to the Magellanic Clouds (*e.g.*, Walborn *et al.* 1995, 2000; Puls *et al.* 1996). Detailed morphological studies of these data revealed extremely fine correspondence between the behavior of the stellar-wind profiles and the optical spectral types for the majority of the normal stars. For instance, the C IV and N V resonance lines have broad, saturated P-Cygni profiles in all O-type spectra until they begin to weaken in mid-O dwarfs, while the lower-ionization Si IV doublet shows no wind effects anywhere on the main sequence, displaying instead a remarkable positive luminosity effect at a given spectral type. The O2 - O3 stars were observed to have the highest terminal velocities (*e.g.*, Howarth & Prinja 1989), and a unique signature of O2 - O3 giant/supergiant spectra is the appearance of an O V λ1371 wind profile. The Magellanic Cloud data display analogous trends, with substantial evidence of the systemic metal deficiency in the SMC.

3.2. *FUSE*

The 900–1200 Å range in O-type spectra offers an even richer array of stellar-wind profiles than the longer wavelengths, with several additional species and higher ionizations, but coverage has been limited to a few bright objects at high resolution or low resolution for fainter objects. This situation has recently been amply rectified by the *Far Ultraviolet Spectroscopic Explorer* (Moos *et al.* 2000), which has assembled an extensive high-resolution archive at those wavelengths for O-type stars in the Galaxy and the Magellanic Clouds. A major atlas of the former has been assembled by Pellerin *et al.* (2002) and of the latter by Walborn *et al.* (2002b). Two panels from the Magellanic Cloud atlas are reproduced here in Figures 2 and 3. They show that the detailed correspondence between stellar-wind morphology and optical spectral types is maintained at the shorter wavelengths. Figure 2 provides an overview of the entire O-type sequence in the LMC, demonstrating the monotonic decline of the highest ionization features with advancing spectral type, while those of lowest ionization display the inverse effect and others of intermediate ionization peak within the range. The highest ionization features (O VI and S VI) are strongest in the O2 spectra, as further illustrated in Figure 3. The SMC spectra display analogous trends, but with weaker features overall. Several quantitative analyses of these data, in combination with those from longer ultraviolet wavelengths and the optical, are providing significant new physical information about the atmospheres and winds of the hottest O-type stars (see papers by P.A. Crowther, D.J. Hillier, and C.J. Evans, these Proceedings).

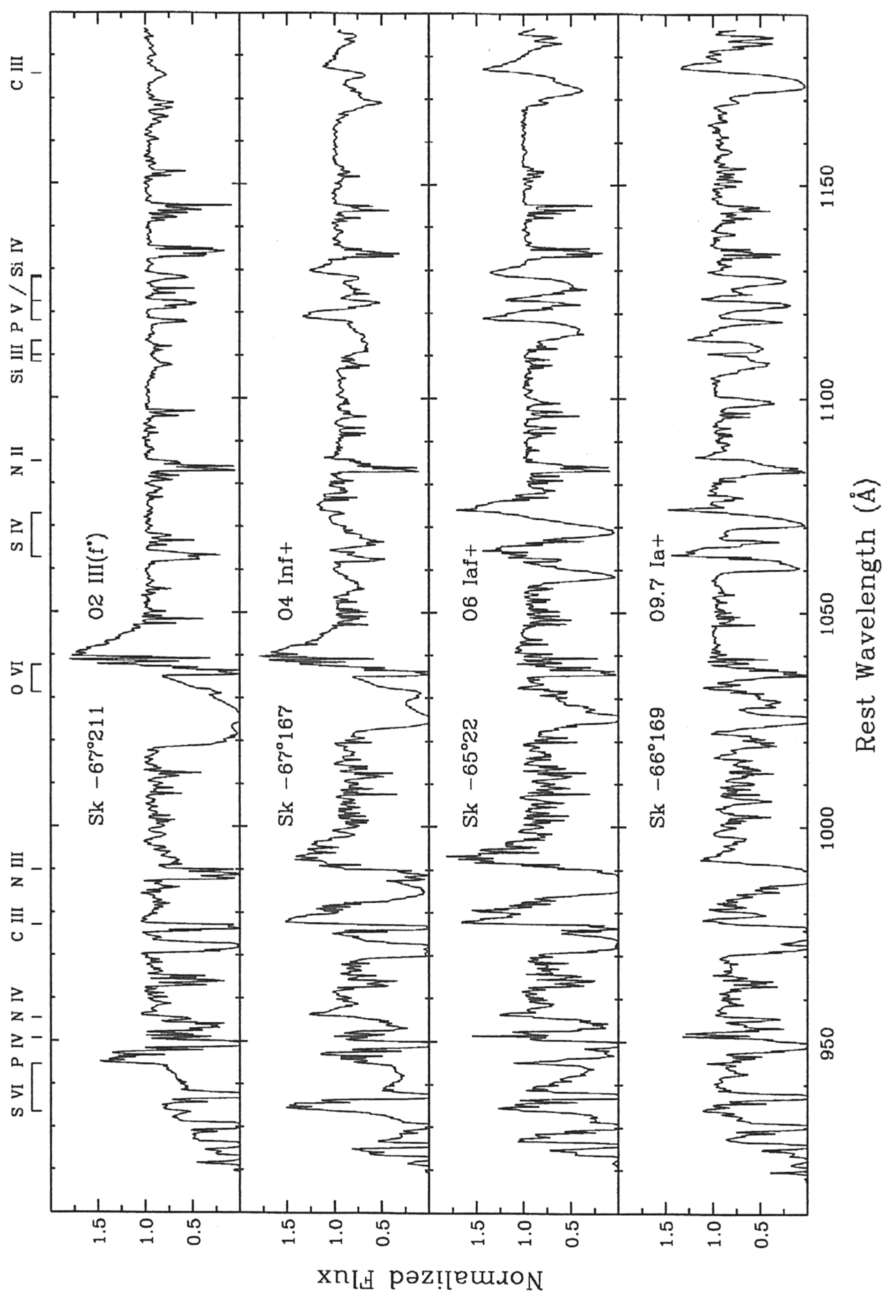

Figure 2. Sequence of *FUSE* spectrograms spanning the O-type spectral range in the LMC and illustrating the systematic behavior of the stellar-wind profiles. Reproduced from Walborn *et al.* (2002b), where further details can be found.

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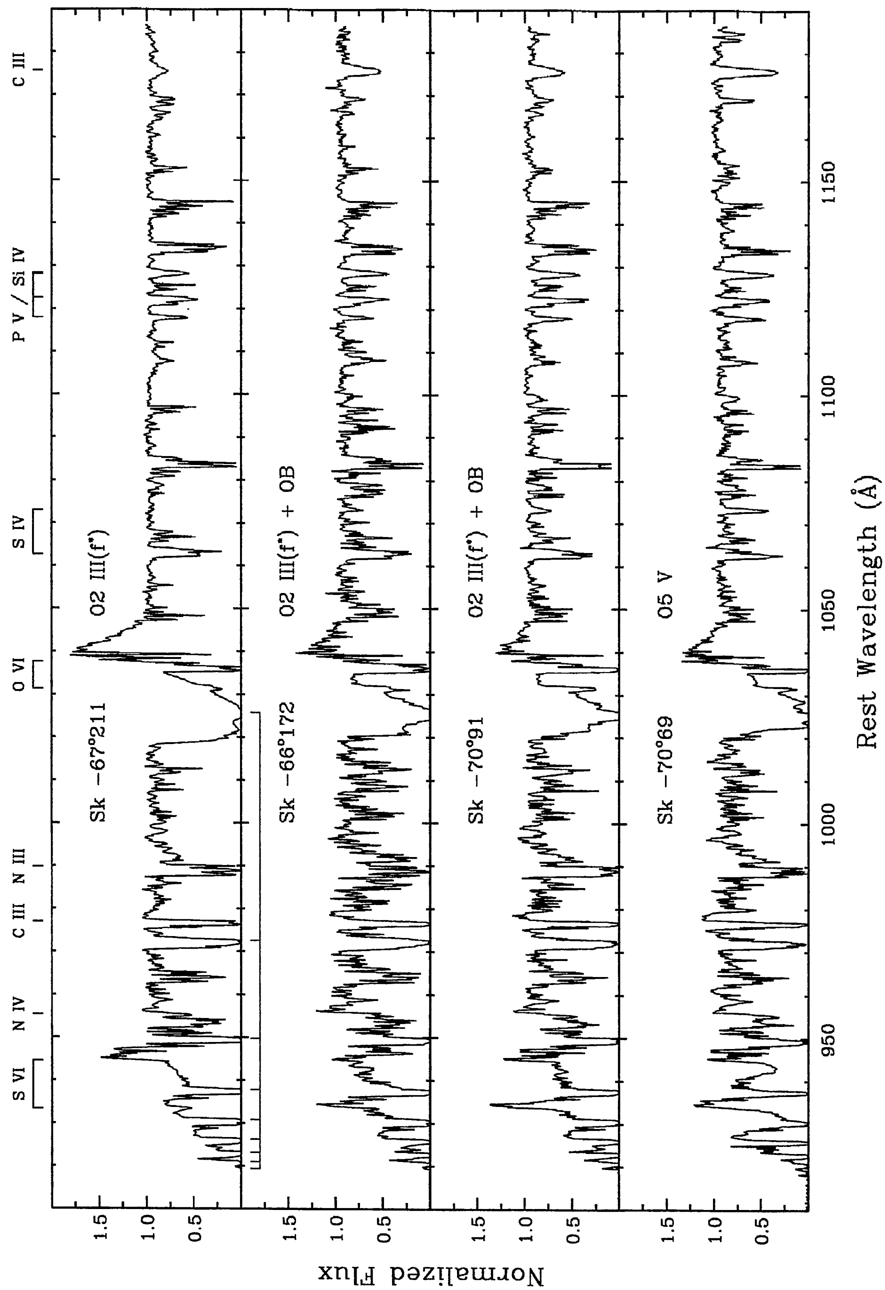

Figure 3. *FUSE* observations of early-O spectra in the LMC, including three of type O2. The two composite spectra are very similar; that of Sk −70° 91 was newly recognized as such in the optical. Reproduced from Walborn *et al.* (2002b), where further details can be found.

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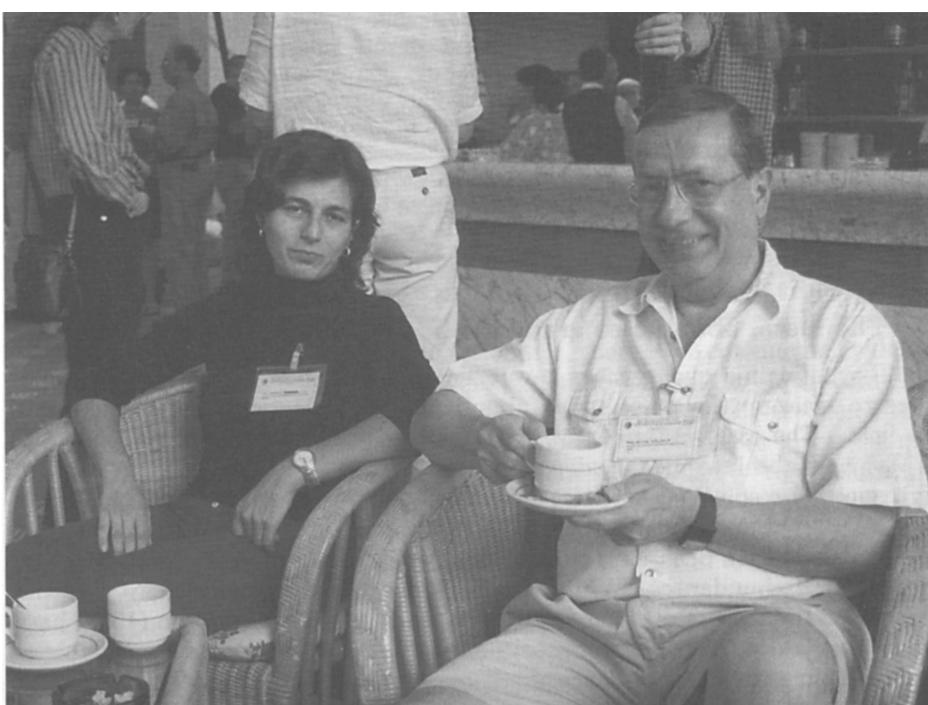
Discussion

GRANT: What are the prospects for extending this work into the near-IR? I ask this because you have demonstrated the importance of spatial resolution and we are seeing more near-IR spectrographs coming on line behind AO.

WALBORN: Indeed, it is essential to extend early-type spectral morphology into the IR, in order to study heavily extinct or young embedded objects (which must be distinguished). That work has already been well advanced by other investigators. Margaret Hanson has established an extensive system in the K-band, with criteria established in objects previously well classified in the optical. Other work in this field by her, Robert Blum, Peter Conti, Don Figer and others has addressed peculiar objects, the H-band, very young objects, and massive clusters at the Galactic Center.

MOFFAT: We've discussed this in private, so let's go public. Would it not be a good idea to morphologically link the strong-line Of stars with the weak-line WN stars, rich in hydrogen, sometimes seen at the highest luminosity in some clusters (*e.g.*, NGC 3603, R 136)? They may be the more massive equivalents of the most luminous Of-stars.

WALBORN: The present study was limited to the empirical description of 'pure' O3 spectra (previously classified as such). In earlier work I discussed intermediate O3 If* /WN-A spectra, through weak-lined to strong-lined pure WN-A (or WNL) types. Empirically, these spectra lie in orthogonal (in terms of envelope/photospheric dominance) and parallel (in terms of ionization) sequences with respect to O2 - O3 spectra. It doesn't appear natural to me to attempt to force these types into a single linear sequence, from the classification point of view. The suggestion to do so appears to be motivated by theoretical interpretation of WNL's associated with O2 - O3's in clusters as more massive 'main-sequence' stars; but that is not a proper classification criterion. Actually, my personal preference is to interpret the WNL's as slightly more massive, more evolved objects than the associated O2 - O3's; this view is not inconsistant with both types still burning H in the core. I do suspect that the M_{bol}'s and masses derived for the WNL's in some studies are overestimated, because the same T_{eff}'s as for the O2 - O3 stars were assumed. In fact, the visual magnitudes may well correspond to lower temperatures at some depth in the optically thick winds of the WNL's.



Charo Villamariz and Nolan Walborn, deserving a break

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