IUE OBSERVATIONS OF CENTRAL STARS

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1. INTRODUCTION

Despite similar evolutionary histories and a common ultimate fate as white dwarfs, central stars of planetary nebulae have surprisingly diverse spectral properties. Their visual spectral types encompass all varieties known for hot stars, including Wolf-Rayet, O and Of, subdwarf O, white-dwarf, and continuous (Aller 1968, 1976), and O VI-emission types (Smith and Aller 1969, Heap 1982). Their spectroscopic temperatures range from less than 30,000°K (e.g. He 2-138, Mendez and Niemela 1979; the WC 11 stars, Houziaux and Heck 1982) to upwards to 150,000°K or more (e.g. NGC 246, Heap 1975; Abell 30, Greenstein 1981). Their atmospheres range from demonstrably helium- and carbon-rich (e.g. the WR stars, Barlow and Hummer 1982, Benvenuti et al. 1982) to apparently normal (e.g. the Of stars, Heap 1977a,b), to helium-poor (e.g. the nascent white dwarfs in Abell 7 and NGC 7293, where gravitational settling appears to have already taken effect, Mendez et al. 1981).

Perhaps this diversity is not surprising when you consider what a wide range in initial mass (approximately 1 to 5 M☉) gets funneled through the central-star sequence. Still, saying that it's not surprising is not the same thing as understanding or verifying it, so I would like to use as the focal point of this talk the question: is (initial) mass a factor in determining the spectral properties of central stars?

To answer this question, it is not necessary (or possible!) to make exact determinations of the mass of each central star. Instead, it is adequate to make mass distinctions among central stars; that is, to show that one group of central stars is more massive than another. We can therefore take advantage of the mass-discrimination inherent

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in evolutionary plots, as first developed by Schönberner (1981). These plots consist of a superposition of observed and theoretical data. The observed data on the plot are the stellar absolute magnitude as a function of nebular radius. Since planetaries have a near-common expansion velocity (assumed here to be 20 km/s), the nebular radius serves as a measure of age since ejection. The theoretical data consist of a stellar mass - age grid, which is derived from atmospheric models and evolutionary models for central stars (Paczynski 1971, Schönberner 1979).

For our observational sample, we shall make use of about sixty galactic planetaries and three planetaries in the Magellanic Clouds whose ultraviolet spectra have been obtained at low-dispersion with the IUE. These observations were obtained by astronomers world-wide (most of whom are here today) over the last four years and are stored in the World Data Centers. Central stars observed by the IUE tend to be optically bright, so most of their spectra have also been studied in the visual and are known to exhibit the full range in spectroscopic properties outlined earlier. The IUE sample incorporates a mixture of galactic populations, as shown in Figure 1 by their spatial and kinematic distribution. In contrast to Pottasch's (1981) sample of faint, presumably more massive central stars, there is a slight leaning of the IUE sample toward the halo population. Only one star in Pottasch's sample, the nucleus of IC 2165, is represented in this IUE sample.

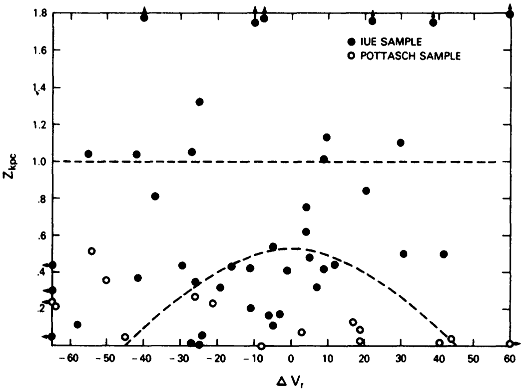

Figure 1. Height Above the Galactic Plane vs. the Deviation of Radial Velocity From That for a Circular Galactic Orbit. The dashed lines show (arbitrary) boundaries of the disk and halo populations.

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The IUE sample does overlap greatly with Schönberner's (1981) sample. It also covers a somewhat broader cross-section of stars by including central stars in large, high-excitation nebulae studied by Kaler (1981) and by retaining central stars in small, optically thick nebulae, some of which have been studied by Kohoutek and Martin (1981). The main reason for retaining stars in optically thick nebulae was to try to get around selection effects that tend against massive stars ($M > 0.65 M_\odot$) in their luminous phase of evolution. The only problem with these objects is that, being ionization-bounded, their observed radii (and hence, age) are smaller than their actual radii (age).

2. THE MASS DISTRIBUTION OF CENTRAL STARS SAMPLED BY THE IUE

The primary observational data for an evolutionary plot are the stellar apparent magnitude corrected for interstellar reddening, distance, and nebular angular diameter. Since the main purpose in constructing an evolutionary plot is to make inter-comparisons among central stars, it is essential to eliminate or reduce systematic errors that would influence the location on the plot of one group of stars with respect to another group , so it is attractive to take advantage of improvements in stellar apparent magnitude offered by the IUE. The attractions of IUE fluxes are consistancy of data obtained by what has turned out to be a very stable spectrophotometer, and an enhanced contrast of the star with respect to the nebula. This contrast enhancement is brought out by a small entrance aperture that rejects extensive nebular contributions and by access to short wavelengths where the stellar flux is at its strongest with respect to nebular continuum emission. As an example, Figure 2 compares the contributions made by the star and surrounding nebula to the observed flux distribution of NGC 2867, a small, bright planetary with a WC/O VI-type nucleus (Smith and Aller 1969). While the visual flux of the star is swamped by nebular emission, the ultraviolet flux of the star is approximately equal in strength to that of the nebula at 1300 Å. The chief disadvantage of IUE fluxes for this purpose is their susceptibility to errors in the amount of interstellar extinction. Errors in the extinction coefficient,c, are magnified six-fold in their effect on stellar magnitude at 1300 Å, so care is required in deriving the appropriate correction, and caution is required in interpreting an ultraviolet evolutionary plot, particularly at the low-temperature region where mass and evolutionary effects are not well discriminated.

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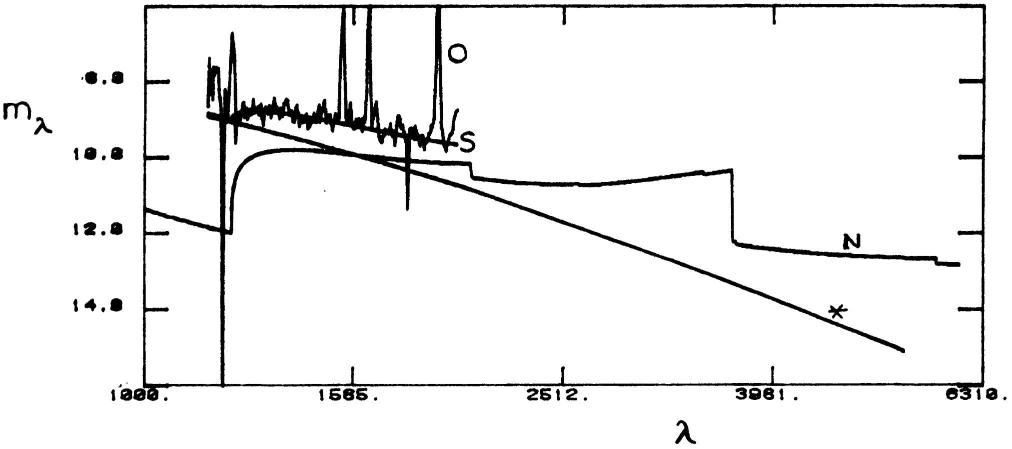

Figure 2. Contributions to the Spectrum of NGC 2867. The ordinate is apparent magnitude [m=-2.5log(flux)-21.1] corrected for reddening. Annotations of the spectra are: O = observed spectrum from the IUE, N = calculated nebular continuous spectrum, * = stellar spectrum as deduced from a blackbody fit to (O-N), and S = sum of the nebular and stellar fluxes.

Also in an effort to reduce systematic errors, while still retaining stars embedded in either optically thick or optically thin nebulae, I have adopted Cudworth's (1974) method of determining distance. This method assumes that the nebular absolute magnitude is a constant for optically thick nebulae, and that the nebular ionized mass is a constant for optically thin nebulae.

An evolutionary plot using ultraviolet stellar magnitudes is shown in Figure 3. Superposed on the observed data is a mass-temperature grid extended from the visual (Schönberner 1981) to the ultraviolet with the use of black-body colors. The immediate inference to be made from this plot is that central stars in optically thin nebulae (identified by Cudworth as having a radius larger the 0.07 pc) are constrained to a sequence implying a narrow distribution about 0.58 M☉ in stellar mass. This finding is in agreement with Schönberner's results, which were based on visual stellar magnitudes and Cahn-Kaler distances. However, central stars in young, optically thick nebulae do not form a bright extension to the sequence, as they do in Schönberner's plot, but instead give the appearance of a high-mass extension to the sequence. This new result is a consequence of two factors that work together to reduce the stellar luminosity of young central stars with respect to

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older central stars on the evolutionary plot: the suppression of nebular contamination from the observed flux, and the use of Cudworth's distance scale. Among this group of young central stars in optically thick nebulae are three central stars in the Magellanic Clouds (shown as squares) for which Maran et al. (1982) derived large stellar masses (>1.0 M⊙) by independent determinations. Although it is difficult to see how such massive stars could be found in their bright stage, their location with galactic planetaries adds force to the interpretation that stars in optically thick nebulae are among the most massive of the sample.

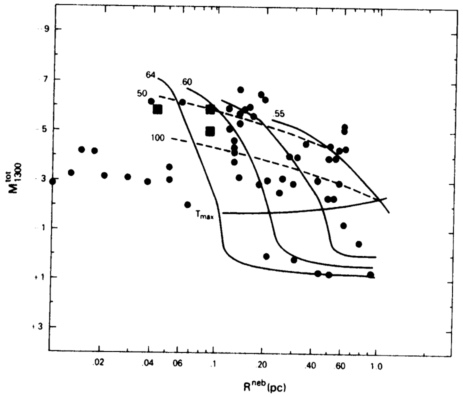

Figure 3. Evolutionary Plot for the IUE Sample of Central Stars in the galaxy (filled circles) and in the Magellanic Clouds (squares). The solid lines show the course of evolution for a star of .65, .60, .57, and .50 M⊙. The two dashed curves show lines of constant temperature = 50,000°K and 100,000°K.

Confirmation of this distribution of stellar masses is highly desirable and should be posssible in the near future. The process of confirmation involves a test for self-consistency: a star's temperature, as read off the mass-temperature grid, should match independent determinations such as its Zanstra temperature, optical color temperature, or spectroscopic temperature. This test not only checks the placement of the M-T grid on the plot, and in doing so, checks the inferred mass of the sample, but the test also -- and most important for our purposes -- checks the shape of the M-T grid, which is essential for distinquishing mass effects from evolutionary (temperature) effects. While desirable, it is too early to carry out a test of this kind, because atmospheric models, upon which both the mass-temperature grid and all independent temperature determinations depend, are deficient in that

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they do not yet take into account the effects of photospheric line-blanketing or alteration of the flux distribution by a wind. As many bolometrically luminous central stars have winds while faint ones do not , we can expect that models that take these effects into account (Hummer 1982; Abbott and Hummer, this volume) will yield an M-T grid with a considerably different shape than the one shown in Figure 3. We can also expect that these model flux distributions, along with observed ultraviolet fluxes from the IUE, will improve the quality of independent temperature determinations.

3. THE MAPPING OF CENTRAL-STAR MASS INTO INITIAL MASS

With such a narrow mass-distribution in the IUE sample of central stars, you might not expect to distinguish mass-effects within the sample. Nevertheless, such effects can be seen (Figures 4 and 1) by the fact that, with few exceptions, stars of high mass, as inferred from the evolutionary plot, are confined to the galactic plane and, by implication, have progenitors of high initial mass, while the low-mass central stars are found in the halo and therefore have low-mass progenitors.

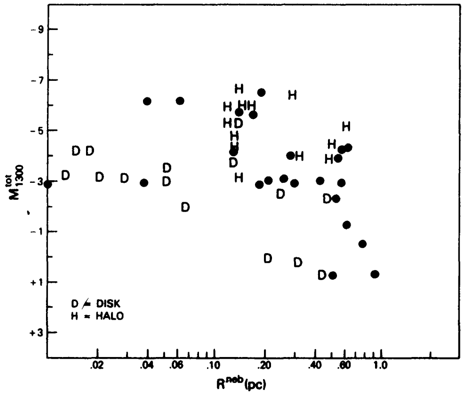

Figure 4. Identification of Halo and Disk Planetaries.

Weidemann (1981) has presented evidence that the amount of mass lost by a red-giant is a strong function of initial mass, with the high-mass giants shedding the largest amount. The segregation of central stars by population type supports this conclusion and, furthermore, implies that the mechanism(s) of mass-loss in central-star progenitors is so highly tuned that, regardless of the initial mass of the progenitor, the final remnant falls neatly into a narrow

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range in mass, with the high-mass (disk) and low-mass (halo) progenitors producing central stars falling at the high- and low-mass ends of the narrow mass range.

The fact that the high-mass central stars are the optically fainter of the sample suggests that still higher-mass objects (M > 0.7 Mo) would be difficult to detect and would be under-represented in any "random" sample of central stars, such as this one.

4. DIFFERENTIATION OF CENTRAL STARS BY SPECTRAL TYPE

The segregation of central stars by population type in the evolutionary plot implies that very small differences in stellar mass among central stars map into large differences in initial mass. There is therefore some justification in examining an evolutionary plot to pursue the question whether initial mass and consequent evolutionary history determines the spectral type of a central star .

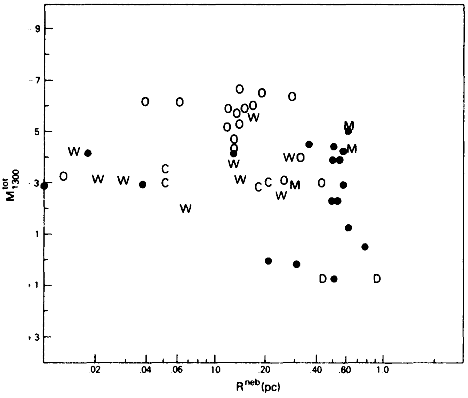

Figure 5. Identification of Stellar Spectral Type. The notation for spectral type is: W=Wolf-Rayet, O=O, Of, and sdO, M=mixed absorption/O-VI emission (cf. Heap 1982), D=white dwarf, and filled circles = unknown.

The evolutionary plot does, in fact, show (Figure 5) some segregation by spectral type in a way that can probably, but not necessarilly, be ascribed to mass. The principal distinction is between the O and WR stars. The O stars are optically bright with M(1300)= -6, while the WR stars are usually about 3 magnitudes fainter. Whether this separation is strictly a mass effect is not clear for two reasons. One

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reason is that both classes of stars have members with winds for which the M-T grid in Figure 3 does not apply. The other is that both groups have members associated with optically thick nebulae, whose actual sizes are highly uncertain. But if the observed radii are within, say, a factor of two of the true radii, then the data suggest that, by-and-large, WR stars are more massive than O stars and that O stars evolve into hot subdwarf-O stars.

One surprise is the lack of distinction between WR and continuous-type central stars. Some continuous-type stars, such as the nuclei of NGC 7662, IC 2165 (in optically thick nebulae) or NGC 6778 and NGC 2022 (in optically thin nebulae) are found in the same region of the evolutionary plot as WR stars. This brings up the question whether such stars really have continuous spectra or whether their spectral features have not been noticed due to masking by the nebula, or due to low-resolution and/or noisy spectrograms. This is an essentially unanswered question at the present time. However, recent spectroscopic studies (Mendez et al. 1981) of stars previously classified as continuous have detected spectral features, and a high-dispersion spectrum of the nucleus of NGC 7662 with the IUE reveals weak, broad emission at C IV 1550, indicative of a weak, high-velocity wind. (The existence of this feature should be confirmed by re-observation.)

In summary, IUE data support Schönberner's assertion that most central stars have masses around 0.58 M☉, although some young, faint stars may be considerably more massive. Despite the narrow distribution in mass, distinctions can be made among stars in this sample, with the following conclusions: (1) low and intermediate-mass stars retain their identity in the sense that stars of higher initial mass produce higher-mass central stars, and (2) Wolf-Rayet stars may be among the most massive stars of the sample.

The reduction of the IUE data was carried out with Dr. Harry Augenson. The nebular contribution of the observed flux of NGC 2867 (Figure 2) was calculated with the use of Dr. J.P. Harrington's computer program, CONTIN.

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APPENDIX: UV Spectra of Selected Central stars Observed By the IUE. The spectra are corrected for reddening and normalized at 1830 Å.

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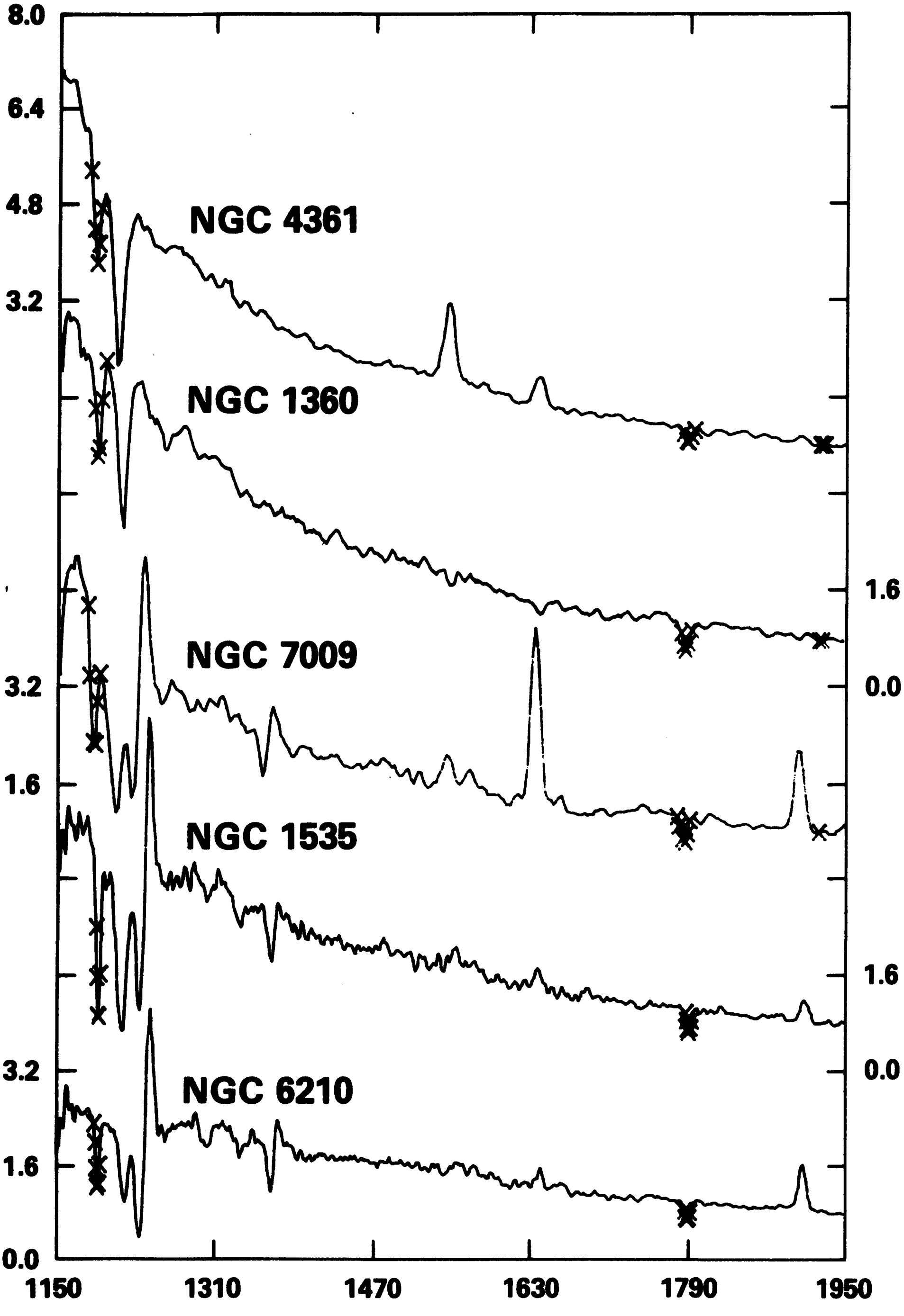

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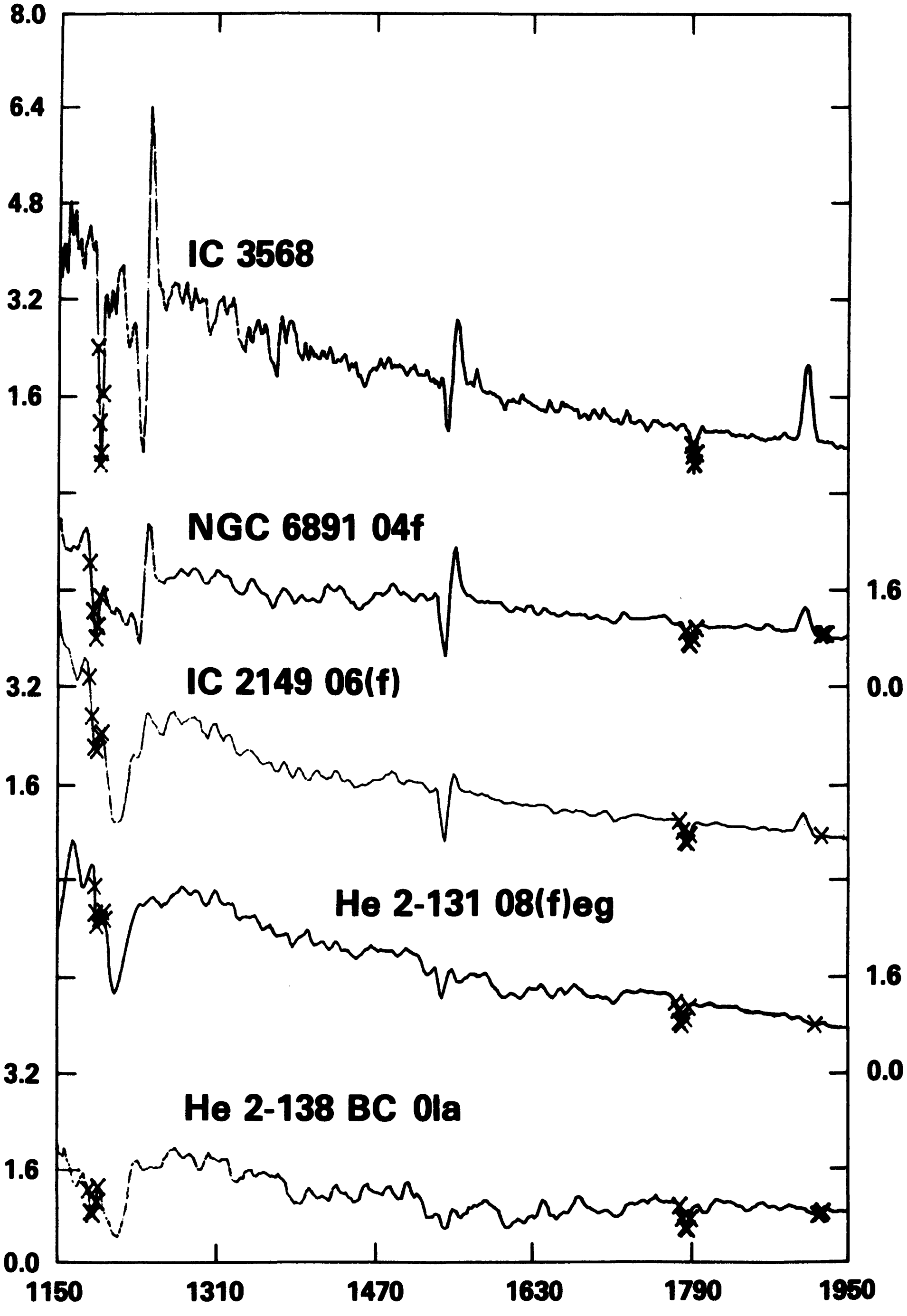

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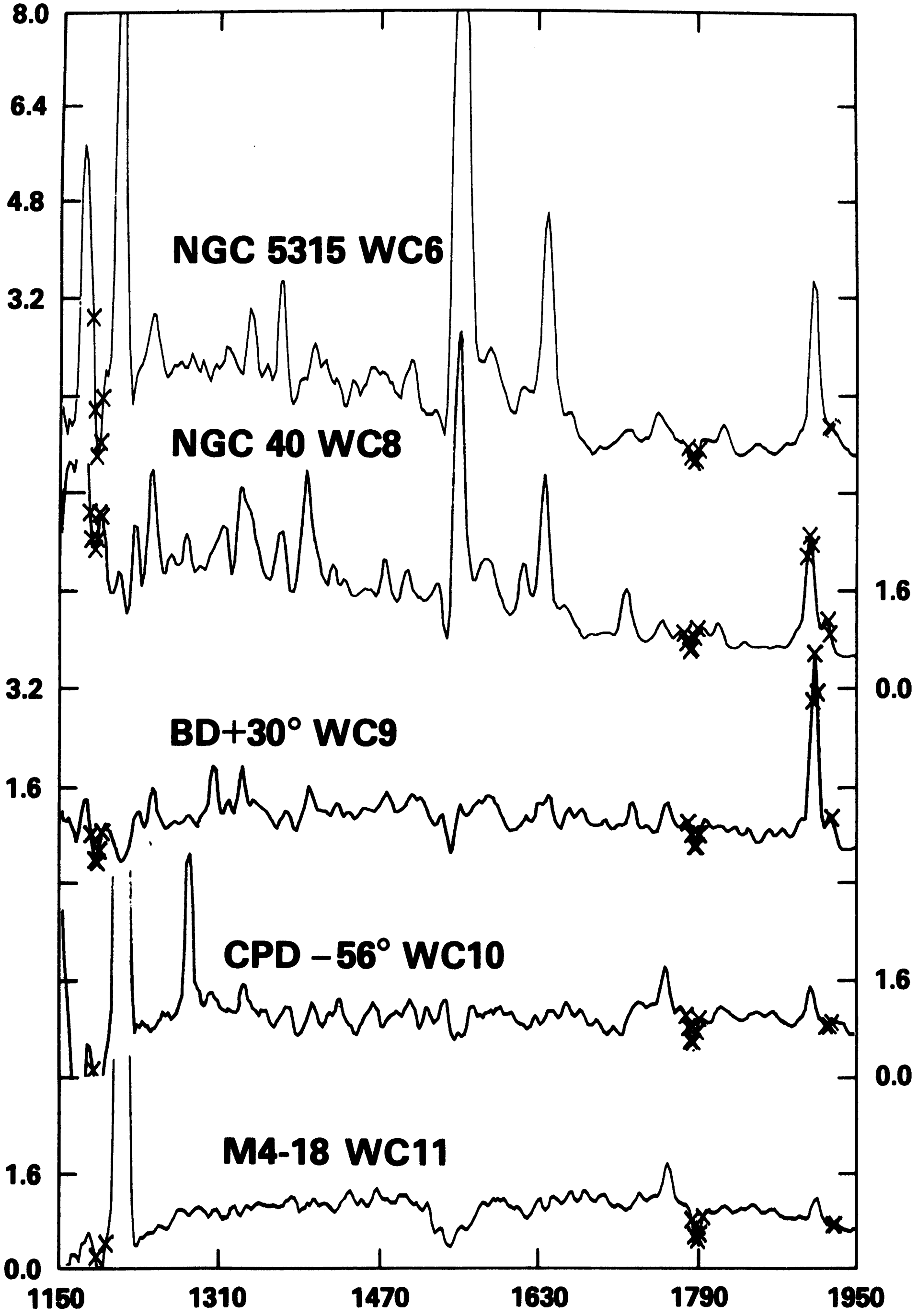

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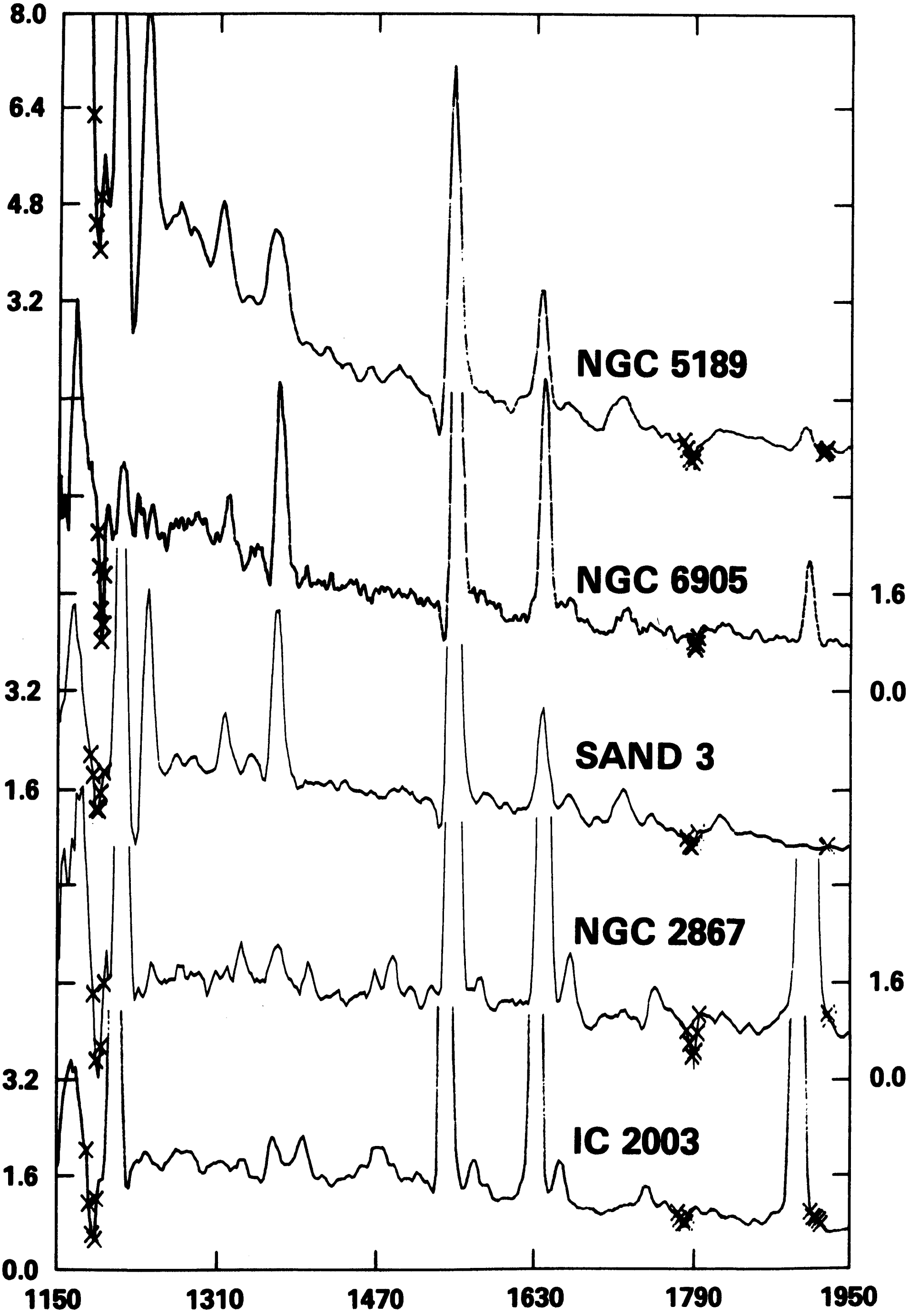

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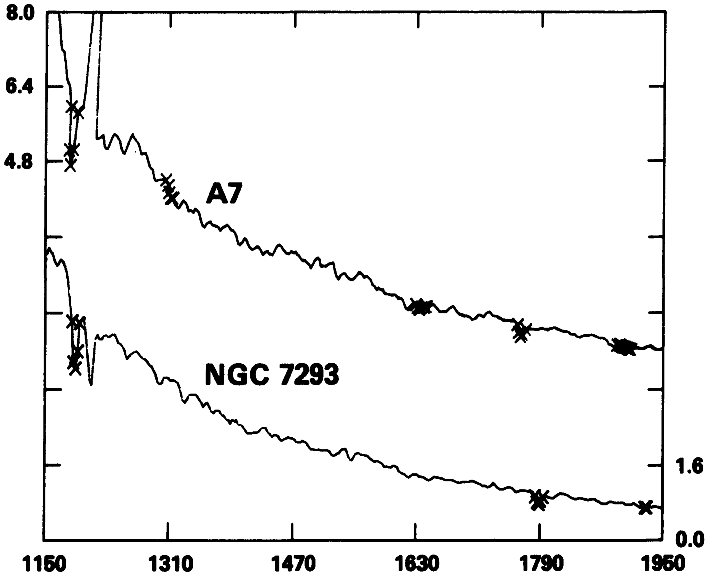

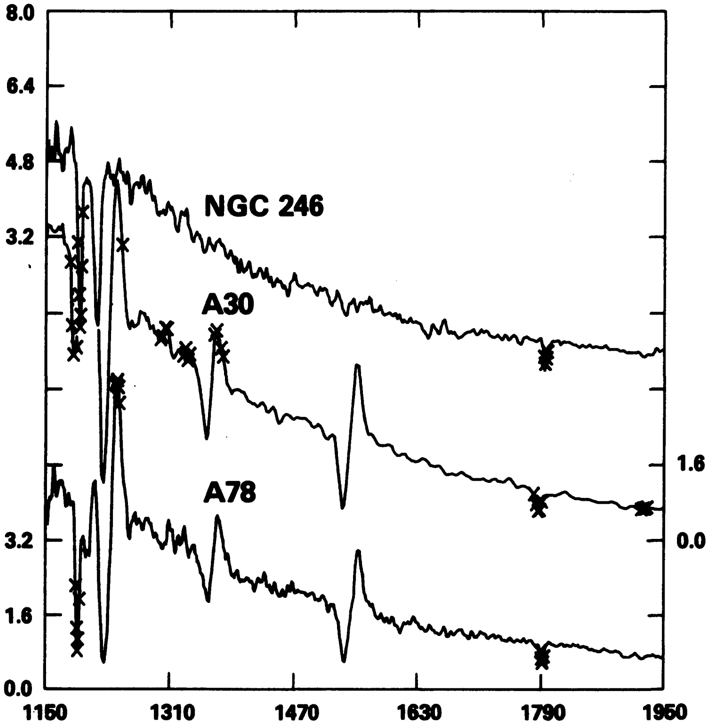

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WEIDEMANN: In connection with your interpretation of the left hand points in your diagrams as a "high mass tail", I wish to point out that, in Schonberner's theoretical plots, the abscissa is actually the time, t. The assumption is that the nebular radius, $R_n \propto t$, corresponding to a constant expansion velocity; but objects with $R_n < 0.1$ pc are optically thick, and $R_n > R_n$ (ionized). It follows that the corresponding points should be shifted to the right. There is a further shift to the right if one considers the expansion velocity to be an increasing function of t in young nebulae (cf. Sabbadin et al., 1982, Astron. Astrophys. 110, 105), since a longer time is required to reach a given R.

KWOK: If the abscissa is, indeed, a time axis, would it not be better to plot against time by dividing each data point by the corresponding expansion velocity?

HEAP: Yes, it would be better - and practical if the expansion velocity of each nebula were known! Most nebulae have expansion velocities of around 20 km s^{-1}, but there are exceptions - in my sample, NGC 2392 has an expansion velocity in excess of 50 km s^{-1}.

SEATON: I hope that I have not given the impression that I thought there were no problems in reconciling optical and ultraviolet photometry with determinations of Zanstra temperatures. The point I wished to make was that I do not think that ultraviolet photometry indicates a need for systematic revision of temperatures obtained by the Zanstra method, as was suggested earlier by attempts to interpret the ANS ultraviolet observations. At the risk of oversimplifying the problem, I would say that optical and ultraviolet colour temperatures are broadly in agreement with Zanstra temperatures.

ALLER: The disagreement between Zanstra temperatures and those appropriate to the spectral class, for objects such as the nucleus of NGC 2392, has been recognised for many years. The binary hypothesis offers a possible solution and certainly holds in some cases (e.g. NGC 1501); but in others, we must consider more sophisticated models with winds, coronae etc. Help is needed from stellar atmosphere experts who can compute model atmospheres not in hydrostatic equilibrium.

MÉNDEZ: Concerning the "continuous" objects, we have recently found that two of the prototypes of this class (NGC 3242 and NGC 7009) are, in fact, absorption-line objects. Therefore, at the present time, it would seem preferable not to use the "continuous" classification in statistical discussions.

HEAP: In my talk, I applied the term "continuous" to those stars classified by Aller (1968) as having continuous spectra in the visual and ultraviolet regions. The central star of NGC 7009 is observed to have a strong wind in the ultraviolet.

RENZINI: If PN with massive nuclei ($M \gtrsim 1\ M_\odot$) do actually exist, we shall have to search for them among those nebulae with visually undetected central stars. Massive PN nuclei should be visually very faint ($M_v > 8$) and should be very hot ($2 \times 10^5 < T_* < 3 \times 10^5$ K). Is there any chance of detecting such stars with IUE?

HEAP: Certainly, the ultraviolet (particularly the region shortward of Lyman α, where the contrast of the star relative to the surrounding nebula should be a maximum) offers some improvement in the possibility

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of detecting massive stars, but the IUE data have not yet been studied systematically with this improvement in mind.

POTTASCH: We have looked at the ultraviolet spectra of several nebulae with faint central stars. Many do not show any continuum, nebular or stellar, in the far ultraviolet. Examples are NGC 6741 and NGC 6445 (although these objects are heavily reddened). For other nebulae, such as NGC 2440, the observed continuum is mainly nebular, which gives an upper limit, $m_v < 16$.

KALER: It is very important that those who observe with IUE and fail to detect a central star should establish an upper limit to the magnitude and publish it. In this way, we can at least place a limit on the Zanstra temperature.

HARRINGTON: Even when a strong continuum is present in IUE spectra, it is sometimes hard to separate the stellar and nebular contributions. In the case of IC 2165, it would appear that about a half of the observed SWP continuum is stellar.

ALLER: Under conditions of good seeing, with the Lick Observatory 3 m telescope I saw a condensation at the centre of IC 2165 that looked very much like a central star.

ISAACMAN: Is the lack of faint central stars in PN of small radius an evolutionary or an observational selection effect (i.e. faint stars would be difficult to detect in young, optically thick nebulae)?

HEAP: It is a selection effect. I chose only those nebulae for which I was sure that the star was detectable.

BOHANNAN: Is it significant that the Wolf-Rayet central stars are all of the WC sub-class? Why are there no WN's?

RENZINI: Post final flash PN nuclei can retain (for a while) a tiny skin containing both C and N - then mass loss removes this skin, exposing the underlying C-rich region, where N is virtually absent. So, stellar evolution theory predicts that there should be a few WCN and many WC nuclei, which, I believe, is observed.

MENDEZ: Concerning the determination of visual magnitudes of central stars, I would like to suggest the use of monochromatic fluxes from photoelectric spectrophotometry, particularly in the case of high surface brightness nebulae. Our observations of NGC 6790 and NGC 7009 show that the magnitudes of Shao and Liller are too bright by about one magnitude. A good visual magnitude is important for the determination of the colour temperatures of central stars.

CLEGG: Following on from this point, I wish to report that, in a survey of PN fluxes, we have found that quoted UBV magnitudes of central stars of small PN were systematically too bright. For NGC 3242, for example, a comparison of optical spectrophotometry (with nebular continuum subtracted), IUE spectra and UBV magnitudes shows the latter to be too bright. A reliable colour temperature can be derived from the merged IUE and optical spectra.

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