WINDS IN HOT, SUBLUMINOUS STARS

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Recent observations with the International Ultraviolet Explorer (IUE) satellite show that two very different types of hot stars have stellar winds: not only do the young, massive OB stars (the subjects of our discussion in this symposium, so far) undergo high-velocity mass-loss, but so also do hot evolved, solar mass stars, among them the central star of planetary nebulae. In this talk, I would like to show ultraviolet spectra of two central stars, the nuclei of NGC 6826 and Abell 78, and to describe how the characteristics of these spectra may be used to derive information concerning winds in these stars and in hot stars in general.

Figure 1 shows the ultraviolet spectra of the two central stars over the wavelength range, 1150-1750 Å. The nominal spectral resolution is about 5 Å (FWHM). The nucleus of NGC 6826 is a tenth-magnitude star having an O3f-type spectrum (Heap 1977) very much like that of the young star, ζ Puppis. You will note that the ultraviolet-spectrum indicates that, like ζ Puppis, the central star has a wind: the resonance lines of C IV λ1550 and N V λ1240 are strong with P-Cygni profiles; and lines from excited levels, such as N IV λ1720, O IV λ1340, and O V λ1370 have P-Cygni profiles or appear as shortward-displaced absorption lines. The apparent terminal velocity of the wind, about 2000 km/s, is somewhat lower than that of ζ Pup, which Lamers and Morton (1976) estimate at 2600 km/s. (I use the term, "apparent" terminal velocity, because I have not taken instrumental line-broadening into account.) The general level of ionization in the wind is similar to that in the wind of ζ Pup. (I should qualify this statement by saying that the OVI resonance lines are not observable with the IUE because of a short-wavelength cutoff in sensitivity at 1150 Å. The inaccessibility of OVI may amount to a serious limitation of the IUE in persuing the problem of stellar winds).

The nucleus of Abell 78 is a thirteenth-magnitude star having an OVI-type spectrum (Greenstein and Minkowski 1964). Such a high-level of ionization is unknown among young hot stars. From Abell's (1966) derivation of the Zanstra temperatures and from Pottasch *et al.*'s

P. S. Conti and C. W. H. de Loore (eds.), Mass Loss and Evolution of O-Type Stars, 99–102.

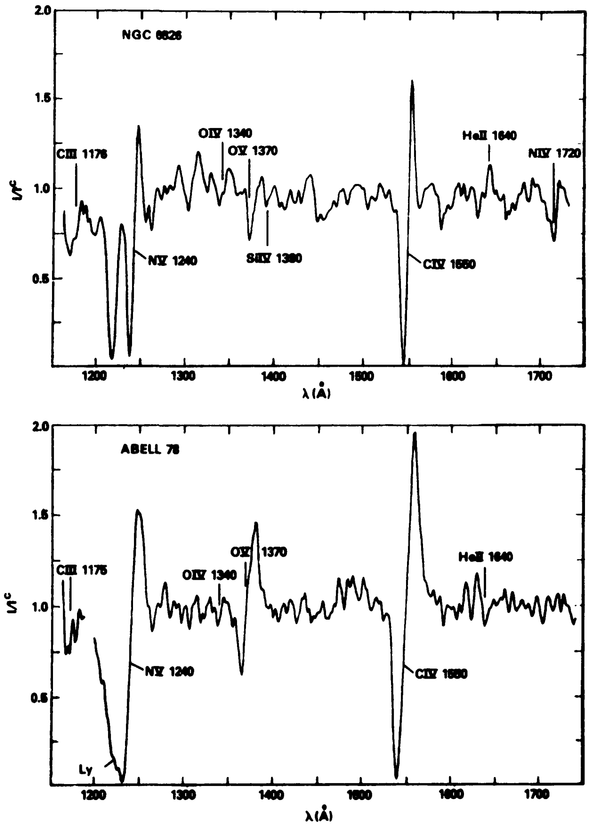

Figure 1. Ultraviolet Spectra of Two Central Stars

(1978) derivation of the ultraviolet color temperatures of Abell objects, I estimate that the central star has an effective temperature in the range, 100,000 - 150,000 °K, and a gravity greater than 10^5 cm/s^2. The ultraviolet spectrum of the central star, as shown in Figure 1, indicates that this star also has a wind, whose apparent terminal velocity is large (about 3400 km/s) and whose general level of ionization is very high.

How is it that these subluminous stars, especially the nucleus of Abell 78 which has such a high-gravity, have a wind? And why is the terminal velocity of the nucleus of Abell 78 significantly larger than that of the nucleus of NGC 6826? These questions can best be answered upon consideration of the stellar luminosity-to-mass ratios ($\mathcal{L}/\mathcal{M}$) and mass-to-radius ($\mathcal{M}/\mathcal{R}$) ratios. We heard earlier this afternoon from Ted Snow that among young hot stars, mass loss appears to set in at a bolometric magnitude, $M_{bol} = -6$. An almost equivalent statement would be to say that mass-loss is characteristic of stars whose $\mathcal{L}/\mathcal{M}$ (in solar units) is greater than about 1600. This statement assumes that mass-losing stars evolve off the main sequence at a constant $\mathcal{L}/\mathcal{M}$ -- an assumption that is only roughly correct, as de Loore et al. (1977) have shown. The reason for restating this

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empirical mass-loss criterion in this way is that it is now applicable to all hot stars including planetary nuclei. Or more strictly speaking, we may now test whether the parameter, $\mathcal{L}/\mathcal{M}$, is the essential criterion for both young massive stars and evolved, solar-mass stars. Referring to the data in the table, we see that the presence of winds in the central stars is consistent with our $\mathcal{L}/\mathcal{M}$ criterion. Furthermore, we see that the apparent terminal wind velocities of the two central stars are at least qualitatively consistent with the view that the terminal velocity is correlated with the escape velocity, which goes as $(\mathcal{M}/\mathcal{R})^{\frac{1}{2}}$.

Star	$\mathcal{L}/\mathcal{M}$	$\mathcal{M}/\mathcal{R}$
ζ Pup	14000	6.3
NGC 6826	24000	0.48
Abell 78	>11000	>2.8

A more general conclusion is that both the presence of stellar winds in hot stars of high $\mathcal{L}/\mathcal{M}$ and the correlation of terminal wind velocity to escape velocity of hot stars are consistent with the radiation-driven theory of stellar winds in hot stars (Castor, Abbott, and Klein 1975).

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DISCUSSION FOLLOWING HEAP

Snow: Could the presence of a strong C IV P Cygni profile while Si IV is absent be attributed to an abundance anomaly, rather than unusually high ionization, in view of the fact that the required ionization energies to form these two species are not very different?

Heap: I'm not sure, but I don't think so: In ζ Pup for example, the C IV absorption is certainly more strongly saturated than is the Si IV absorption, and this star has high ionization in its wind.

Niemela: R. Mendez and I have just finished a study of three central stars of planetary nebulae; and two of them, namely those of He 2-131 of type O8f and He 2-138 of type B0I show blueshifted lines with respect to the nebular velocity, thus suggesting they have expanding atmospheres. So the mass loss effects are seen also in the optical spectra of some central stars of planetary nebulae.

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Heap: The spectrum of He 2-131 is very interesting indeed. Last summer, I published tracings of portions of its optical spectrum. As I remember, lines of He I, N III, H I, etc. all had P Cygni profiles, and the unidentified Of lines at 4486 and 4503 Å are stronger in the spectrum of this star than in any young Of-star spectrum that I've ever seen.

Abbott: The theory of radiatively-driven winds predicts $\dot{M} \propto L(\Gamma/1-\Gamma)^{1-\alpha/\alpha}$, where Γ = Stellar Luminosity/Eddington Luminosity and α is a parameter expected to obey $0.5 < \alpha < 0.9$. Thus, planetary nebulae, where Γ approaches 1, will be predicted to scale to higher mass loss rates for a given luminosity.

Heap: Two stars having the spectral type, say a young Of star and a Of-type planetary nucleus, will have the same L/m ratio and since $\Gamma = (\sigma_c/4\pi Gc)(L/M)$ they will have the same Γ. From this it follows that $\dot{M}/M \propto L/M$ will also be the same according to the radiatively-driven wind theory.

Lamers: According to the radiation-driven wind models, two stars with the same spectral type but different gravities should have different mass loss rates and different terminal velocities: Smaller gravities give larger mass loss rates but smaller terminal velocities. Did you observe these trends?

Heap: Two stars of the same spectral type (including luminosity class) should have the same effective temperature and gravity. Since $g \propto M/R^2$, $v_{esc} \propto (M/R)^{1/2}$ and $v_{term} \propto v_{esc}$, then $v_{esc} \propto R^{1/2}$ for two stars of the same spectral type. Since the nucleus of NGC 6826 must have a considerably smaller radius than ζ Pup, I had expected that the P Cyg profiles in the central star would be sharper than observed. Maybe the central star has a higher temperature and gravity than ζ Puppis.

Bisiacchi: You have shown the spectra of two nuclei of planetary nebulae; do you know if their spectra in the visible region resemble Population I stars?

Heap: The visual spectrum of the central star of NGC 6826 is nearly a ringer for that of ζ Pup. (The main differences between the two spectra is that the line widths of the central star are sharper than those of ζ Pup and the N IV spectrum is different.) The visual spectrum of the central star of Abell 78 has no counterpart among young, hot stars.