RESULTS FROM SPACE

SARA R. HEAP
Laboratory for Astronomy and Solar Physics, Goddard Space Flight Center, Greenbelt MD, U.S.A.

Abstract. Space astronomy has made major and ever increasing contributions to planetary nebula research. Three astronomical satellites – ROSAT, *Hubble*, and EUVE – have been launched since our last meeting five years ago. In addition, SpaceLab experiments flying on the NASA Shuttle have now observed a planetary nebula. After fourteen years, the IUE satellite is still going strong, and IRAS data continue to provide new results on planetaries and their antecedents.

With such a large volume of space data and a broad range in research topics, it is impossible to describe all the results from these instruments. Fortunately, other reviews at this conference by Perinotto (IUE observations of stellar winds) and Zhang (broadband flux distributions) will cover some of these topics. I will limit this review to five topics: (1) the first far-UV spectrum of a planetary, (2) new observations concerning the interaction of a stellar wind and the nebula, (3) the first high-resolution pictures of planetaries made by *Hubble*, (4) new observational evidence on the masses of planetary nuclei, and (5) recent advances in UV spectroscopy of central stars.

Keywords: Planetary nebulae; Stars: atmospheres, early-type, mass-loss, evolution of; UV radiation, X-rays

First Far-UV Spectrum of a Planetary

The far-UV spectral window (from 912 Å to Lyman α at 1216 Å), has special importance for planetaries because it contains: *i)* the O VI resonance doublet, which was detected by *Copernicus* in the winds of virtually all O and WR stars, and *ii)* the Werner absorption bands of molecular hydrogen. In late 1990, the Hopkins Ultraviolet Telescope (HUT) on the SpaceLab mission, ASTRO, obtained a far-UV spectrum of the central star of NGC 1535. Bowers *et al.* (1992) find that the O VI λλ1032,1038 doublet is the strongest wind feature in the spectrum of this hot star (T_{eff}=70,000 °K; Méndez *et al.* 1988). The HUT spectrum also shows strong H_2 absorption below 1110 Å. As yet, Bowers and his colleagues have not been able to determine the relative contributions of the interstellar medium and the nebula to the observed H_2 absorption. However, they note that if all the detected H_2 is in a thin shell around NGC 1535, then an upper limit of 0.007 $M_\odot$ of H_2 is derived.

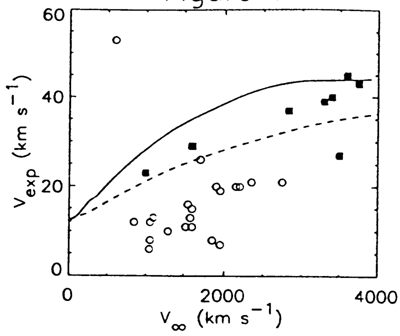
New Observational Evidence Of Wind - Nebula Interactions

Kwok *et al.*'s (1978) interacting wind model leads to two observable consequences: (1) acceleration of the nebula by the high-velocity stellar wind from the hot central star, and (2) production of X-ray emission from the nebula in the collision of the high-velocity wind with the low-velocity nebula. New evidence for both have recently been obtained by space observatories.

R. Weinberger and A. Acker (eds.), Planetary Nebulae, 23–31.

Acceleration of the nebula by the wind. Figure 1, based on data from Patriarchi and Perinotto (PP;1991), shows the relation between the terminal velocity of the wind and the expansion velocity of the nebula. While there is admittedly a large amount of scatter, it is lessened when the composition of the stellar atmosphere is taken into account. Apparently, carbon-rich central stars (■) -- both Wolf-Rayet stars and hot, C-rich subdwarfs like the nucleus of NGC 7094 -- have more rapidly expanding nebulae than do O or sdO-type nuclei (o) with the same wind velocity. A theoretical V_∞-V_{exp}, relation can be computed from the equation of conservation of energy between the fast wind and the expanding nebula at time, t,

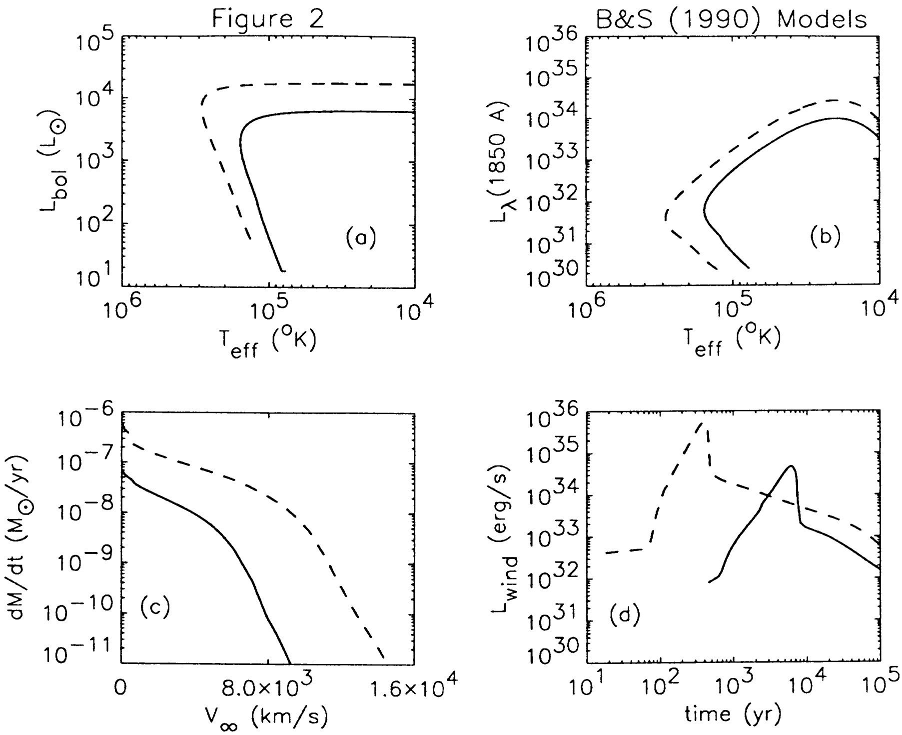
Figure 1



$$\frac{1}{2} f \int_0^t \dot{M}(t')\, V_\infty^2(t')dt' = \frac{1}{2} M_{neb} V_{\exp}^2(t) \qquad (1)$$

where f is the efficiency of converting the kinetic energy of the wind to the nebula. The "luminosity" of the wind, $1/2\ \dot{\mathcal{M}} V_\infty^2$, can be computed from radiatively driven wind theory (Kudritzki *et al.* 1989) as a function of stellar mass, temperature, and luminosity. The stellar parameters, in turn, are given by evolutionary models. Figure 1 also plots the nebular expansion velocity computed with Blöcker and Schönberner's (B&S;1990) $\mathcal{M}$=0.836 (dashes) and $\mathcal{M}$=0.605 (line) models and an assumed AGB wind velocity, V_{exp} =10 km s^{-1}, a constant conversion efficiency, f = 0.3, and nebular mass, $\mathcal{M}_{neb}$=0.2. For a given V_∞, slowly expanding nebulae are associated with more massive stars. Thus, some of the apparent scatter in Figure 1 may be indicative of a dispersion in stellar masses.

I have used B&S's models since only these models take into account the effects of a stellar wind and have the proper initial mass - final mass relation. Figure 2 shows some of the relevant characteristics of their $\mathcal{M}$=0.836 (dashes) and $\mathcal{M}$=0.605 models (line). While a star evolves at constant *bolometric* luminosity on the HR diagram (panel *a*), it fades in the UV-optical region of the spectrum (panel *b*). The course of evolution also causes the terminal wind velocity to increase while the rate of mass-loss decreases (panel *c*). The wind luminosity shows a steep rise as the star evolves along the horizontal track followed by a tapering off as the star becomes a white dwarf (panel *d*). B&S found that after completing its horizontal track, the $\mathcal{M}$=0.836 model actually evolved more slowly than did the $\mathcal{M}$=0.605 model. Consequently, the wind luminosity of the $\mathcal{M}$=0.836 models remains higher than the $\mathcal{M}$=0.605 model, even after 10^4 years (panel *d*). This surprising result is consistent with Dopita and Meatheringham's (1990) inference that nebulae with massive nuclei undergo a rapid acceleration as the star



evolves along the horizontal track and continue to be accelerated as the central star fades.

Extended X-ray emission from planetary nebulae. The first results from the ROSAT all-sky survey have come in, and for the first time, X-ray emission from six planetary *nebulae* (not the stars) has been detected. According to Kreysing *et al.* (these proceedings; 1992), six planetary nebulae, BD +30°3639, NGC 6543, NGC 6853, A 12, NGC 4361, and LoTr 5, were detected by ROSAT. Perhaps these detections should not be surprising, given the ubiquity and strength of the winds from planetary nuclei -- up to 10^{35} erg s^{-1} (panel *d*). What is puzzling is why these six nebulae and not others were seen.

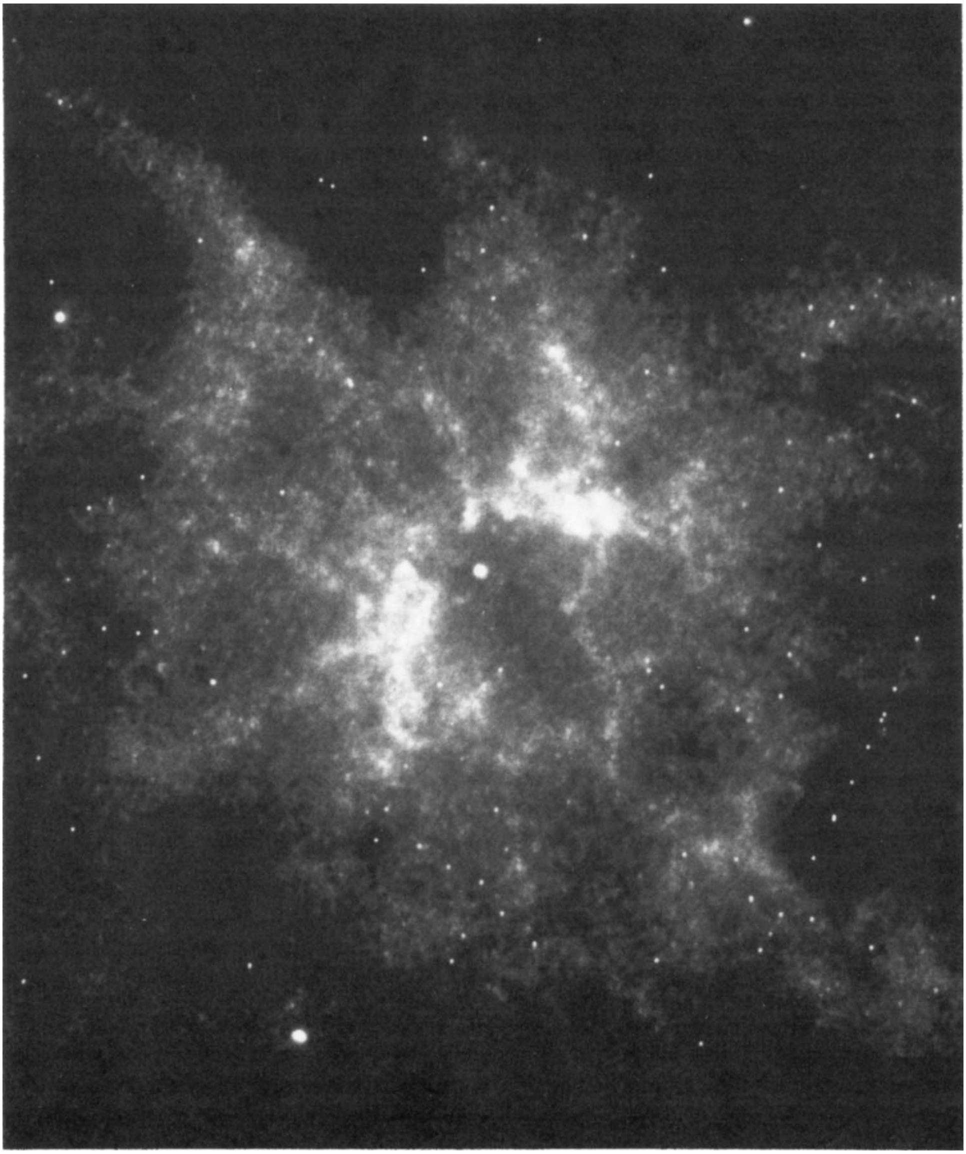
High-Resolution Pictures Of Planetaries From *Hubble*

Despite its problems, *Hubble* is starting to fulfill its long-awaited potential for PN research (*c.f.* Barlow 1989). After image-restoration with the Maximum Entropy Method or the Richardson-Lucy method, structure as small as 0.″06 can be discerned in *Hubble* pictures. Two international groups, one led by Blades and Barlow (these proceedings; 1992) using the Faint Object Camera, and the other led by Dopita (these proceedings) using the Planetary Camera, have obtained [O III]-filter pictures of planetary nebulae in the Magellanic Clouds. Both groups appear to have been surprised that some nebulae were much smaller than expected, and consequently, their nebular expansion ages were much shorter than their presumed stellar evolutionary ages.

Hubble pictures of planetaries in the galaxy are being used to detect faint central stars embedded in bright nebulae and to discern finer detail in the

https://doi.org/10.1017/S0074180900169943 Published online by Cambridge University Press

Figure 3. NGC 2440 as Viewed by the Planetary Camera. The 20-minute observation was broken into two 10-minute exposures, so as to identify and remove cosmic-ray hits. The filter employed was the F517N filter, which transmits continuum light in the spectral range, 5130-5210 Å, as well as N I λλ5198,5200 line emission.



https://doi.org/10.1017/S0074180900169943 Published online by Cambridge University Press

nebulae. As an example, Figure 3 shows a picture of NGC 2440 taken by the Planetary Camera with the F5170N filter, which transmits continuum light from the central star and the emission lines of [N I] λλ5198,5200 doublet from the nebula. For the first time, the central star is clearly visible. The Zanstra temperature of the central star, T_z = 200,000 °K, derived from the *Hubble* images is in accord with previous ground-based measurements using image-subtraction techniques (Heap & Hintzen 1990).

The Continuing Saga Of Central-Star Masses

At the last meeting in Mexico City, the Munich group announced a new, spectroscopic method of determining the masses of planetary nuclei (Kudritzki and Méndez 1989, Méndez *et al.* 1988) which is independent of distance and nebular parameters. By comparing the effective temperature and gravity with evolutionary tracks plotted on a T_{eff}-log g plane, they were able to derive the mass of a central star. Later, Pauldrach *et al.* (1988) showed that it was possible also to derive the stellar mass from the terminal velocity of the wind as measured on IUE spectra. Since the last meeting, the Munich group lowered its mass-estimates upon finding that the gravities might be underestimated due to filling in of the hydrogen absorption lines by nebular emission and/or wind emission ((McCarthy *et al.* 1990, Gabler *et al.* 1989). Even so, these estimates of stellar mass are still often higher than others (Table 1), and they show a disturbing correlation with temperature.

Since the last meeting, two new distance-independent methods of estimating stellar mass have been developed. One method (Heap, these proceedings; 1992) identifies massive central stars on the basis of UV fading by the central star over the lifetime of IUE. According to Blöcker and Schönberner's (1990) models, a star evolving along the high-luminosity, horizontal track increases in temperature at a rate,

$$dT_{eff}/dt = 4080\, \mathcal{M}^{10.63} \quad \text{°K per year.} \qquad (2)$$

As the temperature increases at constant bolometric luminosity, the UV-optical luminosity decreases as shown in Panel 2*b*, since a greater fraction of the flux goes into the unobservable extreme-UV. The higher the mass, the faster the fading. Altner and Heap (these proceedings) used the IUE to look for signs of optical fading in planetary nuclei. In fact, they did detect UV-optical fading in just those central stars that Méndez *et al.* (1988) had identified as the most massive in their sample ($\mathcal{M}$(spec)≥0.77). However, their optical fading masses, listed as $\mathcal{M}(\dot{L}_{uo})$ in Table 1, are significantly lower than the spectroscopic masses.

The other new distance-independent method makes use of nebular fluxes measured by IRAS and radio telescopes. Zhang and Kwok (these proceedings; 1992) calculate what stellar mass would allow a star to evolve to the observed Zanstra temperature in the time that the nebula has faded to its observed surface brightness. Their results listed under the column *M(T,SB)*, are also shown in Table 1.

Comparing masses in Table 1 is a little like comparing distances (see Terzian, these proceedings): there is no clear best method. Furthermore, there is sometimes agreement among the methods (usually with the hot subdwarfs), and sometimes, strong disagreement (usually for the Of-type stars. See other papers in these proceedings on the Of-type nucleus of NGC 6826 by Gabler *et al.*, Becker & Butler, Altner *et al.*, and the nucleus of NGC 2392 by Heap, Altner & Heap). Nevertheless, there is some convergence in mass estimates compared to five years ago.

Advances in UV Spectroscopy

With the steady accumulation of UV spectra of planetary nuclei from the IUE has come the realization of the importance of the iron-group elements (Dean and Bruhweiler 1985, Schönberner and Drilling 1985, Hubeny *et al.* 1991). Absorption lines of ionized iron and nickel dominate the UV spectra of all central-star spectra on the horizontal track of the HR diagram *i.e.* not subject to gravitational settling. According to Dreizler and Werner (1992; these proceedings), not only do the iron-group lines affect the appearance of the UV spectrum: they also affect the structure of the stellar atmosphere, so as to produce deeper and broader H and He line profiles. Because the profiles of H and He lines form the observational basis for determining temperature, gravity and helium abundance, their finding has profound implications for future spectroscopic analyses.

The quality of UV spectra has undergone a dramatic boost with the new spectra obtained by the GHRS and FOS spectrographs on the Hubble Space Telescope. As an example, Figure 4 (next page) shows a 10-Å segment of the UV spectrum of the sdO star, BD +75°325, obtained by the GHRS in June 1992. With a resolving power of 15 km s^{-1}, this GHRS spectrum has twice the resolution of IUE, and its high signal-to-noise, S/N=70, is totally unattainable by IUE. While not a planetary nucleus, BD +75°325 represents an important test-case for atmospheric modeling. According to Hubeny (1992), who is analyzing the spectrum, NLTE line-blanketed models will be necessary to match the observed spectrum .

With its rich UV spectrum and very sharp lines, the spectrum of BD +75°325 is also an excellent test-case for UV line-lists and associated atomic data and spectral synthesis codes. In anticipation of high-resolution GHRS spectra, Becker and Butler (these proceedings; 1992) made NLTE calculations of the formation of Fe V lines. They found that a full non-LTE treatment of line formation is necessary to interpret the Fe V spectrum observed in O and sdO-type central stars.

In a recent survey of planetary nuclei and hot subdwarfs, Feibelman and Bruhweiler (1990) claimed the detection of Fe VII in the UV spectrum of BD +75°325 as well as in the spectra of planetary nuclei with temperatures as low as 35,000 °K. In the case of BD +75°325, the GHRS spectrum confirms the presence

Comparison of Stellar Mass Estimates

ID	T_{eff} (1)	M(spec) (2)	$M(V_\infty)$ (3)	$M(\dot{L}_{UV})$ (4)	M(T, SB) (5)	M(OFD) (6)
A 36	95x10^3	0.61	--			0.59
NGC 7293	90	0.55	--			0.66
NGC 7009	82	0.69	0.64		0.63	0.66
NGC 4361	80	0.55	--		0.59	0.62
NGC 1360	75	0.55	--		0.56	0.58
NGC 3242	75	0.68	0.63		0.61	0.65
NGC 1535	70	0.67	0.61		0.61	0.63
IC 3568	51		0.57		0.61	0.55
NGC 6891	50	0.77	0.63		0.61	0.58
NGC 6210	50	0.77	0.55		0.63	0.66
NGC 6826	50	0.81	0.63		0.59	0.59
NGC 6629	47	0.77			0.61	
NGC 2392	47	0.77	0.8	0.71	0.59	0.65
IC 4593	36		0.68	0.72		0.59
IC 418	36	0.82	0.65	0.73	0.68	0.66
Hu 2-1	33	0.67			0.68	0.67
He 2-108	33	0.87	0.67		0.58	
He 2-131	33		0.75	0.71	0.68	
He 2-138	27	0.87		0.74	0.61	0.67

2) Mass and T_{eff} derived from non-LTE spectroscopic analysis by Méndez *et al.* (1988) and McCarthy *et al.* (1990).

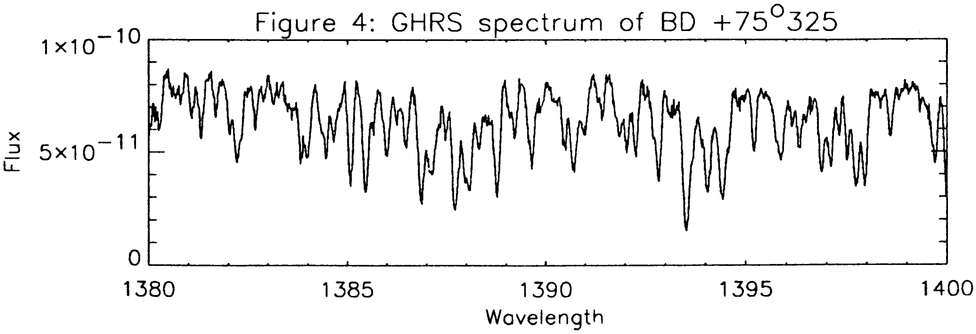
3) Calculated mass assumes wind parameters, α=0.709, δ=0.052, β=1.0; T_{eff}=0.9 x that listed here (to account for wind blanketing); $V_\infty = 0.85\ V_{edge}$, where V_{edge} is taken from Heap (1986), Pauldrach *et al.* (1988), and Patriarchi and Perinotto (1991).

4) Optical fading mass from Altner and Heap (these proceedings)

5) Mass derived from T_{eff} and nebular surface brightness, from Zhang and Kwok (1992).

6) Mass based on position of star on an optical fading diagram (OFD); Heap and Augensen (1987), but see also Weidemann's (1989) corrections, which result in lower masses.

https://doi.org/10.1017/S0074180900169943 Published online by Cambridge University Press



of an absorption feature near the Fe VII laboratory wavelength, but theoretical calculations by Hubeny indicate that the observed features are in reality due to Ni V, not Fe VII lines. For planetary nuclei in general, Tweedy (1992) disputes many of F&B's detections and identifications, and he maintains that Fe VII lines are present only in stars as least as hot as 70,000 °K.

The UV spectrum has importance not only for estimating abundances but also for determining the fundamental properties of very hot central stars, where the He I/He II ionization balance cannot be used to derive effective temperature. For example, Werner and Koesterke (1992) determined the properties of the nucleus of Abell 78 through a comprehensive analysis of its UV-optical spectrum. They found that one of the best handles on temperature was the ratio of strengths of O V λ1371/O VI $\lambda\lambda$3811,3834. As another example, Tweedy and Napiwotzki (1992), obtained an approximate value of the effective temperature of the central star of the nearby, large planetary, S 216, from the ratio of strengths of Fe VI to Fe VII lines in the UV spectrum. Clearly, while UV spectroscopy is still in its infancy, it is a field of great potential.

References

Barlow, M.J. 1989, in *Planetary Nebulae* (IAU Symp. No. 131), ed. S. Torres-Peimbert, (Kluwer: Dordrecht), p. 319
Becker, S. & Butler, K. 1992, *Astr. & Ap.*, in press
Blades, J.C., Barlow, M.J. *et al.* 1992, preprint
Blöcker, T. & Schönberner, D. 1990, *Astr. & Ap.*, 240, L11
Bowers, C. *et al.* 1992, in preparation
Dean, C. & Bruhweiler, F. 1985, *Ap.J. Suppl.*, 57, 133
Dopita, M. *et al.* 1992, preprint
Dopita, M. & Meatheringham, S. 1990, *Ap.J.* 357, 14
Dreizler, S. & Werner, K. 1992, in *The Atmospheres of Early-Type Stars*, ed. U. Heber, C.S. Jeffery, (Springer-Verlag: Berlin), p. 436
Feibelman, W.A. & Bruhweiler, F.C. 1990, *Ap.J.*, 357, 548

Gabler, R. *et al.* 1989, *Astr. & Ap.*, 226, 162
Heap, S. R. 1986, ESO-SP-263, p. 291
Heap, S.R. 1992, *Ap. J.*, submitted
Heap, S. R. & Augensen, H. J. 1987, *Ap.J.*, 313, 268
Heap, S.R. & Hintzen, P. 1990, *Ap.J.*, 353, 200
Hubeny, I. *et al.* 1991, *Ap.J.*, 397, L33.
Hubeny, I. 1992, private communication
Kreysing, H.C. *et al.* 1992, *Astr. & Ap.*, in press.
Kudritzki, R.-P. *et al.* 1989, *Astr. & Ap.*, 219, 205
Kudritzki, R.-P. & Méndez, R. 1989, in *Planetary Nebulae* (IAU Symp. No. 131), ed. S. Torrest-Peimbert, (Kluwer: Dordrecht), p. 273
Kwok, S. *et al.* 1978, Ap.J., 219, L25
McCarthy, J. *et al.* 1990, *Ap.J.*, 351, 230
Méndez, R. *et al.* 1988, *Astr. & Ap.*, 190, 113
Patriarchi, P. & Perinotto, M. 1991, *Astr. & Ap., Suppl.*, 91, 325
Pauldrach, A. *et al.* 1988, *Astr. & Ap., 207, 123*
Schönberner, D. and Drilling, D. 1985, *Ap.J. Lett.*, 290, L49
Tweedy, R. 1992, *M.N.R.A.S,* in press.
Tweedy, R. & Napiwotski, R. 1992, M.N.R.A.S., in press
Weidemann, V. 1989, *Astr. & Ap., 213, 155*
Werner, K. & Koesterke, L. 1992, in *The Atmospheres of Early-Type Stars*, ed. U. Heber, C.S. Jeffery, (Springer-Verlag: Berlin), 288
Zhang, C.Y. & Kwok, S. 1992, *Astr. & Ap. Suppl.*, submitted

R. WEINBERGER, A. ACKER, P.J. HUGGINS

https://doi.org/10.1017/S0074180900169943 Published online by Cambridge University Press