ULTRAVIOLET SPECTRA OF PLANETARY NEBULAE AND THEIR CENTRAL STARS

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1. INTRODUCTION

Antediluvian UV observations of planetary nebulae were made using rockets and the ANS, TD-1 and Soyuz-13 satellites: this work is reviewed by Gurzadyan (1978) and Pottasch (1978); see also Bohlin et al. (1978), Pottasch et al. (1978) and Lutz and Carnochan (1979).

With IUE came the deluge. To my knowledge, IUE observations have been made of 54 planetaries, and work continues by many groups, on making observations and reducing and interpreting the data. The present report describes some preliminary results.

2. NEBULAR SPECTRA

NGC 7662 is typical of a fairly high excitation planetary. Harrington et al. (1979a) have obtained a number of exposures in order to measure fluxes in weak and strong lines. Figure 1 shows its combined short- and long-wave spectra, at low resolution: log flux is plotted against log wavelength (see section 5.1 below) and the strongest lines have been truncated. The main features are: O III Bowen lines; He II Paschen lines and He II Balmer α at λ1640; forbidden lines of [Ne IV] and of [O III] (blended with C II] λ2326); intercombination lines of C II], C III], N III], O III], N IV] and O IV] (Si III] can also be detected in the wings of the strong C III] lines); resonance lines of C IV and Si IV. The O IV] and Si IV blend is resolved in a high dispersion spectrum by Heap (1979). The He II λ2307 line is blended with a line which may be C III λ2297.

The reddening may be obtained from (radio)/(Hβ) and from He II $\lambda\lambda$4686, 2733 and 1640 (optical observations are used to obtain the λ4686 flux for the IUE large slot): the adopted reddening constant is c=0.25. The accuracy of the photometry is checked by comparing fluxes in all the observed He II lines with calculated fluxes, reddened with

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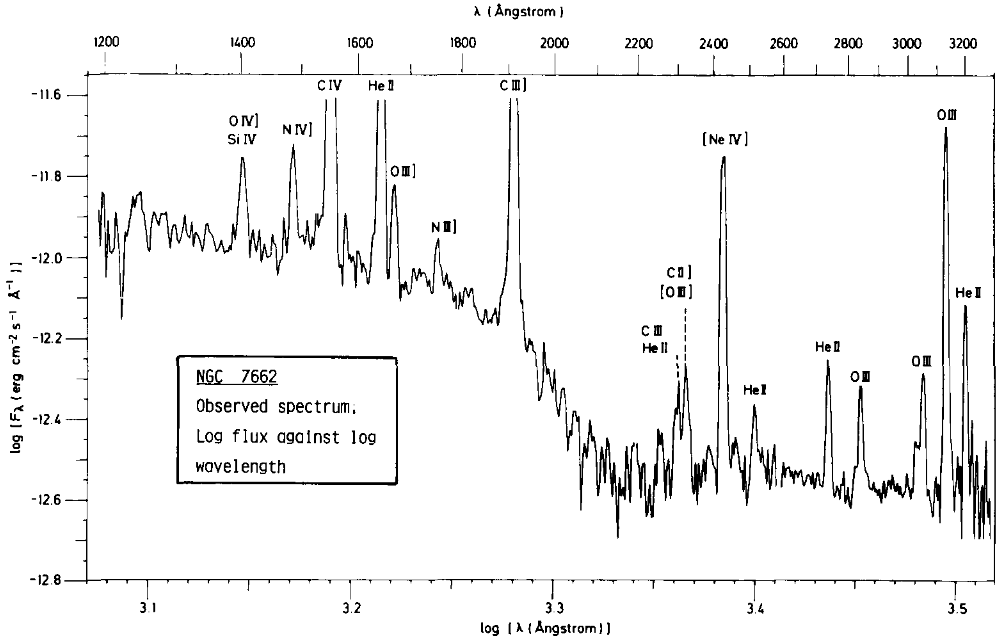

Figure 1

c=0.25 (see Table 1). For other lines in NGC 7662, Harrington et al. have compared observed fluxes with those from a detailed computer model.

For low excitation planetaries the strong lines include Mg II λ2800, C II] λ2326, [O II] λ2470 and C III] λ1908.

Table 1. He II Line Fluxes in NGC 7662

λ	Flux in 10^{-12} ergs cm^{-2} s^{-1} Calc.	Obs.
4686	26.1	27.2 ± 5.0
3203	9.0	7.4 ± 1.5
2733	4.0	4.2 ± 0.7
2511	2.0	1.8 ± 0.3
2383	1.2	1.2 ± 0.5
2307	0.7	blend
2253	0.5	0.6 ± 0.2
1640	97.8	93 ± 6

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3. DIAGNOSTICS FOR ELECTRON TEMPERATURES AND DENSITIES

3.1 [O III] and O III]. The flux in O III] λ1664 may be compared with that in [O III] λ4363 and λλ4959, 5007. At lower densities this provides a check on the determination of T_e (O III) but at higher densities O III ^1D suffers collisional de-excitation and the intensity ratios for the O III] and [O III] lines become sensitive to T_e and N_e. Using these lines, Perinotto et al. obtain T_e = 12,700 K and $N_e = 6 \times 10^4$ cm^{-3} for NGC 7027.

3.2 O IV]. Since He^+ and O^{+2} have nearly equal ionization potentials, all oxygen more highly ionized than O^{+2} will be in the He^{+2} region. Neglecting O^{+4} and higher stages we obtain $N(O^{+3})/N(He^{+2}) = [N(O^+)+N(O^{+2})]/N(He^+)$ where the quantity on the right-hand side is known from optical observations. The ratio F(O IV] λ1402)/F(He II λ1640) depends on $N(O^{+3})/N(He^{+2})$ and the usual exponential factor in T_e. This gives a temperature T_e (O IV). Harrington et al. obtain, for NGC 7662, T_e (O IV) = 14,100 K compared with T_e (O III) = 12,500 K. The difference between these temperatures is consistent with that predicted by models and is important for the interpretation of other UV lines, such as C IV λ1550.

3.3 [Ne IV]. The $^2D \rightarrow {}^4S$ transition in [Ne IV] gives lines at λλ2421.8, 2424.5 with relative intensities sensitive to N_e. From a high dispersion spectrum, Lutz and Seaton (1978) obtain $N_e = 1.1 \times 10^4$ from the [Ne IV] lines in NGC 7662.

3.4 C III]. The $^3P_J \rightarrow {}^1S_0$ transitions in C III] give an intercombination electric dipole line at λ1908.73 (for J=1) and a more highly forbidden magnetic quadrupole line at λ1906.68 (for J=2), with relative intensities sensitive to N_e for $N_e \gtrsim 10^4$ cm^{-3} (Loulergue and Nussbaumer, 1976). A high dispersion spectrum of NGC 7009 by Köppen and Wehrse (1979) shows λ1907 to be stronger than λ1909, which would be expected with $N_e < 10^4$ cm^{-3}. Flower, Nussbaumer and Schild (1979) have observed the young planetary IC 4997 and the possible protoplanetaries V 1016 Cyg and HM Sge. In IC 4997, λ1907 is much weaker than λ1908, and the ratio gives $N_e \simeq 5\times10^5$ cm^{-3}, while for the protoplanetaries λ1907 does not appear at all, giving $N_e > 10^6$ cm^{-3}.

Another remarkable feature of the V 1016 Cyg and HM Sge observations is the great width of the C III] and C IV lines, indicating expansion velocities of about 100 km s^{-1}.

4. CARBON ABUNDANCES

UV observations are of great importance for the determination of C abundances. Table 2 gives results for three planetaries. For the low excitation planetary IC 418 one observes C II] λ2326, [O II] λ2470 and C III] λ1908 but no C IV nebular emission. The UV fluxes can be compared with optical fluxes using the known branching ratio for [O II]

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Table 2. Carbon Abundances, log{C}, on the Scale log{H} = 12

Nebula	log{C}	Reference
IC 418	8.7	Harrington et al. (1979b)
	8.85	Torres-Peimbert et al. (1979)
NGC 7662	8.5	Harrington et al. (1979a)
NGC 7027	9.1	Perinotto et al. (1979)

λ2470 and λλ7320, 7330. The abundances of Table 2 are obtained using temperatures T_e (N II) and T_e (O III) (Torres-Peimbert et al. consider that allowance for temperature fluctuations will increase log{C} to 9.0, and give C^{+2}/H^+ from UV observations in closer agreement with the value deduced from C II λ4267 interpreted as a recombination line). The C abundance in NGC 7662 is obtained with the aid of a computer model. For NGC 7027, Perinotto et al. allow for a reduction in the observed C IV flux due to internal dust absorption, and use T_e (O III) for interpretation of the C IV line. The results for C abundances indicate some C/O enrichment but not by large factors.

5. CENTRAL STARS

5.1 Ultra-violet Colour Temperatures. Pottasch et al. (1978) have attempted to derive ultra-violet colour temperatures, T(uvc), from wideband (150 Å) ANS observations. Figure 2 illustrates the difficulties involved: the flux of Figure 1 for NGC 7662 has been corrected for reddening and the nebular continuum has been subtracted; the two smooth curves, for T(uvc) = 50,000 K and 100,000 K, are not very different and the IUE observations provide little justification for choosing one in preference to the other.

5.2 Spectral Features. The UV spectra of the central stars are very varied. The star of NGC 7662 has no observed spectral features in the optical and no obvious features in the UV. NGC 6543, on the other hand, is very rich in P Cygni lines (Fig. 3): the terminal velocity is $V(\infty) = 2150 \pm 100$ km s^{-1} (Castor et al. 1979) and the He II lines at λ1640 and λ4686 are of stellar origin.

The C IV lines at λλ1548.2, 1550.8 have different profiles in different objects. Figure 4 shows these lines in a high dispersion spectrum of IC 418 (Clavel and Flower 1979): compared with NGC 6543, the lines have less emission and a lower terminal velocity. A high dispersion spectrum of NGC 6210 (Köppen and Wehrse 1979) shows C IV to be entirely in absorption.

5.3 Mass Loss Rates. Castor et al. (1979) discuss a technique for the analysis of P Cygni profiles observed at low resolution using the moments W_0 and W_1 where

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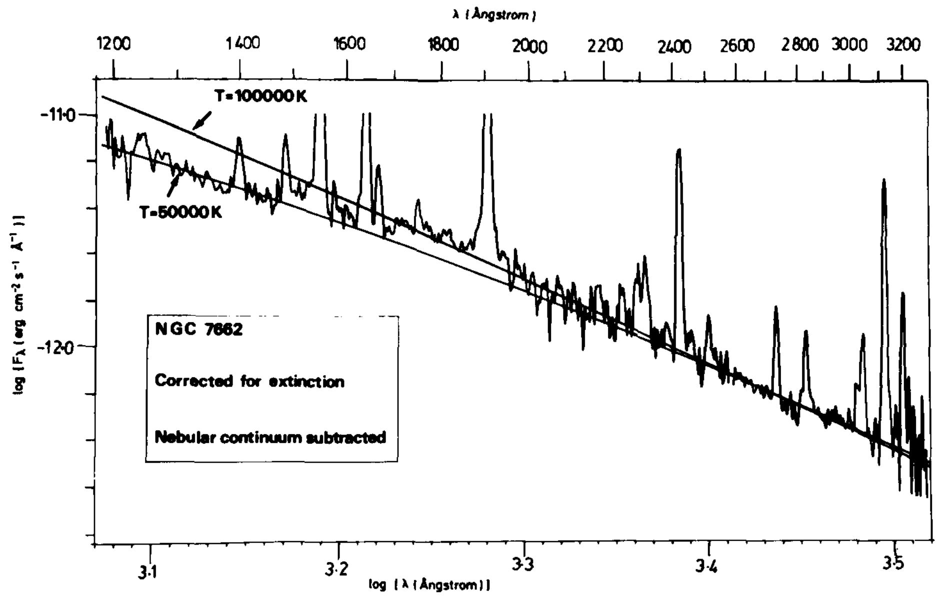

Figure 2.

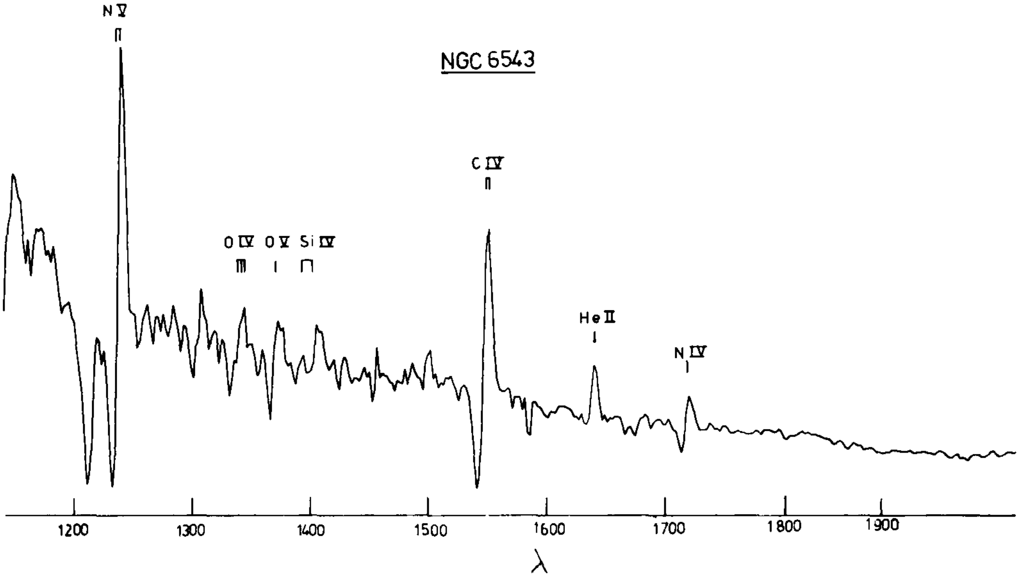

Figure 3.

$$W_i = \left(\frac{c}{\lambda_o V(\infty)}\right)^{i+1} \int \left(\frac{F_\lambda - F_c}{F_c}\right) (\lambda-\lambda_o)^i \, d\lambda \ :$$

W_0 is proportional to the equivalent width; for a profile with nearly equal amounts of absorption and emission, W_0 is small and W_1 large.

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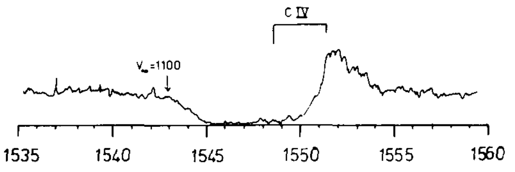

Figure 4. The C IV feature at high dispersion in IC 418.

Using the equations given by Castor (1970) one obtains expressions for W_0 and W_1 in terms of the quantities usually employed in Sobolev theory. For optically thin lines, W_1 is proportional to f(ion) × $\dot{M}$ where f(ion) is the abundance of the ion concerned, relative to the abundance of the element; and $\dot{M}$ is the mass-loss rate. For NGC 6543, Castor et al. use the O IV and O V P Cygni lines, assume f(O IV) + f(O V) = 1, and obtain $\dot{M} = 1.0 \times 10^{-7}\ M_\odot\ yr^{-1}$.

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DISCUSSION:

L. H. Aller: With image-tube scanner observations of IC 418 obtained at Lick, we find an intensity of λ4267 which, when interpreted with our theoretical models, gives a carbon abundance in agreement with the results of Lutz et al.

M. Dworetsky: I have recently found data in published sources which can be used to deduce the absolute oscillator strength of Hg II λ3984 from laboratory measurements. The abundance from this line agrees with that which you find from the resonance line in the same star. Therefore NLTE cannot be invoked to explain the strength of λ3984. There is one cool HgMn star, HR 7775, which shows Ga I and Ga II in its spectrum. This is a violation of the general trend of Ga-anomaly vs. T_{eff}.

G. Doschek: Why are the C III λ1909 and C IV λ1550 lines so wide, i.e., the non-thermal motions are ≈ 100 km/sec while most expansion velocities determined from visible observations of planetary nebulae are ≈ 20 km/sec?

M. Seaton: I showed results of Flower, Nussbaumer, and Schild. Dr. Nussbaumer might like to answer the question.

H. Nussbaumer: The region emitting C III may expand differently from the region emitting C IV (the difference is actually not very large). However the difference in the deduced velocity may also be due to the way we measured the line width. We measured it close to the bottom of the line, and in our spectra the C III 1909 is higher than the C IV doublet. Also our numbers are only lower limits for the maximun expansion velocity.

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