ADVANCES IN ULTRAVIOLET OBSERVATIONS

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Several groups have been involved in recent years in making ultraviolet observations of planetary nebulae from rockets and satellites. About 30 or 40 nebulae have been measured up to the present, some with reasonably high spectral resolution, more with band pass filters of 100 Å or more in width. All measurements have large diaphragms (or slitless systems) so that usually the nebula and the central star are observed together (there are large nebulae for which this is not true). The photometric accuracy of the later observations is quite good, usually better than 20%.

The earliest measurements were made by the OAO-2 (Holm, 1972). Only preliminary results have been published up to now, and the photometric measurements are only given with respect to the bright O star, S Mon. They refer to rather wide spectral regions. The Soyuz experiment reported the measurement of a single nebula (Gurzadrian, 1975) with spectral resolution of about 25 Å. Rocket measurements of two nebulae have been made by the Goddard SFC group with a spectral resolution of 35 Å (Bohlin et al., 1975, 1977). The photometric accuracy of the last flight (NGC 7662) is superior to that of their first flight. A survey experiment on the European satellite TD-1 was able to measure 8 nebulae with a 27 cm telescope (Carnochan and Wilson, 1977). This experiment had no spectral resolution for planetary nebulae because they are so faint that sufficient signal-to-noise could be obtained only by averaging over spectral regions several hundred angstroms wide. There is a single exception to this: NGC 6543 lies so close to the ecliptic pole that repeated observations were made (more than 2000). A preliminary discussion of 633 scans has been made (Boksenberg et al., 1975). The resultant spectrum is shown in Fig. 1.

The most complete and accurate measurements available at present are those made by the Netherlands Astronomical Satellite ANS (Pottasch et al., 1977, 1978). These authors have made photometric measurements of about 30 planetary nebulae with filters from 50 Å to 200 Å wide at the following wavelengths: 1550 Å, 1800 Å, 2200 Å, 2500 Å and 3300 Å. A complete description of the instrument has been given by Van Duinen et al. (1975).

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Both a narrow band (50 Å) and a wide band (150 Å) filter are located at 1550 Å, and a comparison of the two measurements permits a determination of the strength of the C IV doublet at 1550 Å. Aside from this doublet, the measured flux is usually primarily continuum emission.

We shall discuss in turn: A. the accuracy of the measurements; B. the possibility of using the measurements to determine extinction; C. the separation of the nebular component from the stellar component; D. the interpretation of the stellar flux in terms of a stellar temperature; E. the interpretation of the nebular flux; F. the interpretation of the C IV emission lines; G. central stars with A type spectra.

A. Accuracy of the measurements

The most accurate photometry is available in the ANS measurements. The reproducibility of these measurements is better than 2% for the stronger sources. A more serious problem is the absolute calibration and these errors up to 20% may be possible. In this light, it is interesting to compare the ANS values for NGC 6543 with those of the same nebula, independently calibrated by the TD-1 observers. This is shown in Fig. 1 where the ANS measurements are plotted as rectangles whose height is the observed flux and whose width is the filter width. The agreement is extremely good: the ANS value at λ1800 Å showns the worst disagreement, a difference of 6%. The other measurements are within 3% of each other.

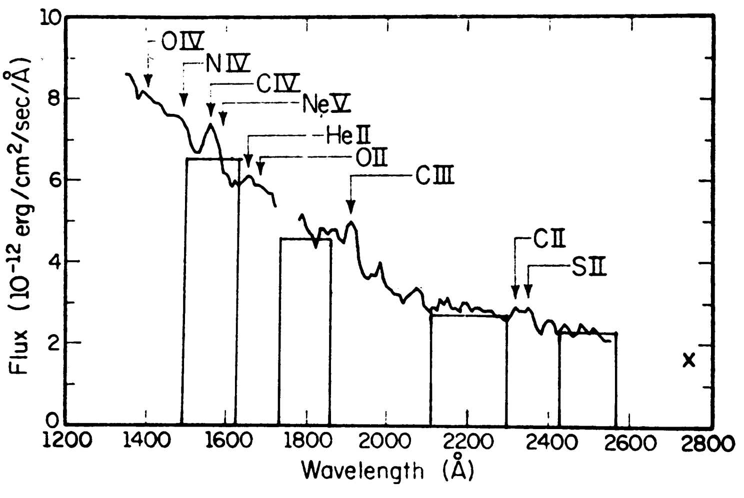

Fig. 1. Comparison of the TD-1 spectrum of NGC 6543 (star plus nebula) with the ANS measurements, illustrating the agreement of the independent calibrations.

We may also compare the ANS measurements of NGC 7662 with those of the Goddard SFC for this nebula. These latter measurements have a higher error but there is agreement within this error for all bands except λ2200 Å, where the Goddard measurements are 25% lower. To investigate this difference further we have compared the measurements of the 7 other nebulae which the TD-1 and ANS have in common. In particular we have compared the λ2200 Å and λ2500 Å bands of the ANS with the λ2350 Å TD-1 measurement. No systematic difference as large as 25% was found.

It is likely that the present measurements are accurate within 10-20%, with the value at λ2200 Å the most uncertain.

B. The possibility of using the λ2200 measurement to determine extinction

The purpose of the band at λ2200 was for the determination of extinction in all objects, since the extinction is known to peak at this wavelength. The bandwidth of the ANS measurement (200 Å) is considerably smaller than the extinction feature (350-400 Å). The extinction can be determined if two conditions are met:

1) the intrinsic spectrum of the object is relatively smooth over the wavelength interval 1700 Å - 2600 Å;

2) the intervening (interstellar) medium is characterized by a uniform extinction curve whose properties are known.

Neither of these conditions can be generally shown to be true but arguments can be given which indicate that these conditions are met. Regarding point 1), we can say something about the intrinsic spectrum for those nebulae which are free of extinction (as deduced from a comparison of radio and Hβ emission, or from the Balmer decrement). Five nebulae, mostly at higher galactic latitude are free of extinction, and another four have very little. All these nebulae show a continuous run of fluxes for all five channels, without any trace of a peak or dip at λ2200. This argues strongly that condition 1) is met. Regarding point 2), this is the usual assumption which is made when obtaining the extinction (e.g. from the Balmer decrement) and it gives consistent and acceptable answers. The only difference here is the wavelength region, since the OAO II measurements have shown that the extinction curve for certain objects differs considerably from the average curve in the far ultraviolet. This effect is usually not very pronounced at wavelengths greater than 2000 Å, but there are exceptions, and this uncertainty must be born in mind.

The observed dip in flux at λ2200 Å is thus a measure of the extinction and can be expressed at E_{B-V} (the details of this are given in Pottasch et al., 1977). We can check the above reasoning by comparing the value of extinction obtained in this way, to that obtained from the ratio of the Hβ flux to the radio flux. This comparison is shown in Fig. 2, where the E_{B-V} obtained from the ultraviolet measurements is plotted as abscissa and the Hβ/radio ratio as ordinate. (This is a slightly improved version of the diagram published by Pottasch et al., 1977). Individual nebulae are shown as points in the diagram. The good correlation of the extinction determined in these two ways is strong support for the approximate validity of the assumptions used. A further confirmation comes from the slope of the line drawn through the points in this diagram. The slope is a measure of the ratio of the total absorption to Hβ (or to the visual using the Whitford reddening curve) to E_{B-V}, and gives a value of $A_V/E_{B-V} \simeq 3 \pm 1$. This value is that which is found in numerous other ways to characterize the interstellar medium, and it seems very unlikely that this value would have been found if the assumption of a uniform extinction curve were not valid.

C. Separation of the nebular emission from the central star emission

The ratio of nebular emission to central star emission in the ultraviolet varies from object to object. In general, the radiation from the central star increases more rapidly toward the ultraviolet than the nebular radiation, and there is a tendency that the central star emission dominates the spectrum more often than not. How does one separate the two components? There are two possibilities, which can be used in combination to perform this separation.

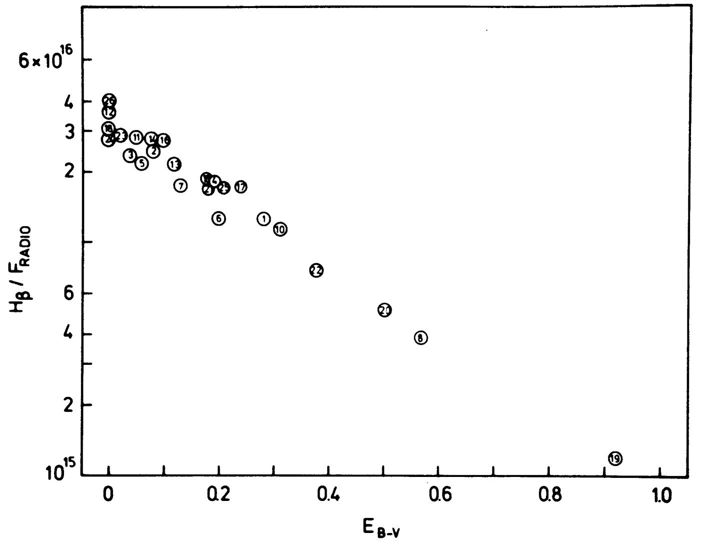

Fig. 2. Comparison of the E_{B-V} value determined from the λ2200 Å dip with the Hβ/radio continuum ratio for individual nebulae. The numbers refer to the following nebulae: 1) 2371-2, 2) 2392, 3) 1535, 4) 418, 5) 3242, 6) 4361, 7) He2-131, 8) 6629, 9) 6751, 10) 6572, 11) 4593, 12) 7293, 13) 7009, 14) 6210, 15) 6891, 16) 6853, 17) +30 3639, 18) 6826, 19) 7027, 20) 7008, 21) 7662, 22) 40, 23) 246, 24) 6543, 25) 3568, 26) 3587.

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First, for most of the objects, one has photometric measurements of the central star (Shao and Liller, 1977). A very small extrapolation of the U flux enables one to make a rather dependable estimate of the central star intensity at λ3300. A comparison with the ANS measurement at λ3300 yields the nebular flux at this wavelength. Since the nebular spectrum is often known at these wavelengths, we can separate the nebular flux in line and continuum flux. Once the continuum nebular flux at λ3300 is known we can predict the nebular continuum flux further in the ultraviolet since the continuum is due mainly to two-quantum emission and Balmer continuum emission, both well studied processes.

Secondly, we can predict the nebular continuum emission from the same theory, but beginning with the measured Hβ flux. Both procedures depend on an approximate knowledge of the electron temperature in the nebula. Both should lead to the same result, and allow a check to be made against possible errors in UBV magnitudes and Hβ fluxes.

Further, correction must be made for nebular line emission. There are, fortunately, few strong lines in the ANS bands, as can be judged by the 3 spectra cited above. The C IV lines in the λ1550 band can be measured separately in the narrow band. No strong lines apparently are present in the λ1800 and λ2200 bands, and sometimes the NeIV line at λ2440 may be important in the λ2500 band. The strength of this line can be calculated from the measured strength of the NeIV line at λ4725. In only a few cases is the correction for this line (λ2440) important.

D. Central star emission

In at least 20 cases the central star emission can be determined to an accuracy of better than 25% after all corrections have been made. These results have been published in detail (Pottasch et al., 1978). The spectra, from λ1550 to λ5500, are often, but not always, characterized by single blackbody temperatures. This is especially true of the hotter stars and the Abell objects. It is also roughly true for stars with O type spectra, although sometimes there is a tendency for the spectrum to turn down for the shortest wavelengths in these objects. It is certainly not true for stars with a Wolf-Rayet type spectrum, whose emission is quite flat. It is also not true for stars with a continuous spectrum, where in the two cases measured strong departures from a blackbody spectra are marked. The following table gives the best fitting blackbody temperature for several cases in which departures of the observational points are less than 25% over the entire wavelength range from λ1550 Å to λ5500 Å.

It may be remarked that the relative flux measurements of central stars which show an O type spectrum is indistinguishable from actual O type stars, and that the blackbody temperatures found are very similar to effective temperatures given in the literature for actual O stars. In contrast, all 4 Abell objects measured showed considerably higher blackbody temperatures (75,000°K or higher) as did several other objects with

O VI or unknown spectrum, but which have in common with the Abell objects the fact that the nebula is very large. This is probably an evolutionary effect: larger, and presumably older, nebulae become hotter.

Nebula	Spectral type	T	Nebula	Spectral type	T
NGC 1535	05	45,000°K	IC 4593	07f	34,000°K
IC 3568	05	44,000°	IC 418	07f	32,000°
NGC 6629	0	44,000°	NGC 1360	sd0:	100,000°
NGC 6210	06	38,000°	NGC 7293	-	95,000°
NGC 2392	07f	36,000°	NGC 246	O VI	100,000°
NGC 6826	06f	30,000°	A31	sd0	75,000°
NGC 6891	07	30,000°	A33	sd0	75,000°

Another aspect of the ultraviolet measurement of the central star is the ability to observationally determine the bolometric correction. Especially for the lower temperature stars, much or most of the energy is longward of λ912 Å. The present measurements extend in a few cases to λ1350 Å and in most cases to λ1500 Å. An extrapolation to λ912 Å is most reliable for those objects whose known spectrum can be represented by a blackbody, although even for the other objects the most important part of the gap to λ912 Å has now been bridged.

E. Nebular continuum emission

Because the central star increases in intensity considerably more rapidly toward the ultraviolet than the nebular continuum, it becomes increasingly difficult to measure the nebular continuum. In two cases where the nebula was very large, it was possible to point at a position far enough from the central star so that it was excluded from the diaphragm (NGC 7293 and NGC 246). Only a portion of the nebula was then measured, which has two disadvantages: 1) that the nebular emission was very weak, and 2) that no comparison with the Hβ flux can be made.

Other methods are also available. Since the OAO II and the ANS used different size diaphragms, the difference between these measurements for nebulae larger than the ANS diaphragm is a measurement of a part of the nebular emission. This method does not at present give very accurate results, since only a preliminary calibration of the OAO II data is available.

Another method can be used in the few cases where the nebular emission is substantially larger than the flux from the central star. If an estimate can be made of the stellar emission, the nebular can be determined. This can be done for NGC 6853 which clearly has a very steep stellar spectrum.

The results confirm that the nebular continuum is essentially that predicted by the sum of Balmer continuum and 2 quantum emission. The 'measurements' (after the above corrections) are not sufficiently precise to allow a good determination of the electron temperature of the gas.

F. Emission lines of C IV

The spectra of 3 nebulae have been measured to about λ1400 Å. The measured line emission is probably due only to the nebula, although in NGC 6543 the central star may make a small contribution. The three strongest lines are those due to [CIII] λ1909, HeII λ1640 and the C IV doublet at λ1550. The latter is by far the strongest line. It has also been measured by the ANS, as described above, for these 3 nebulae, and 7 others as well. The intensities measured by the different groups for the 3 common nebulae are in good agreement. For 20 other nebulae measured by the ANS, an upper limit to the strength of the C IV lines can be given.

The interpretation of the C IV line strength in terms of an abundance of carbon is still in an early stage. If we compare the predictions of Flower (1968), based on detailed models of 4 nebulae, with the measurements we obtain the following results:

Nebula	Predicted C IV	Measured C IV
NGC 1535	1.3×10^{-10}	$\leq 4 \times 10^{-11}$ erg cm^{-2} s^{-1}
NGC 2392	3.3×10^{-10}	3.6×10^{-11}
NGC 7009	3.1×10^{-10}	$\leq 6 \times 10^{-12}$
NGC 7662	2.2×10^{-10}	3.3×10^{-10}

As can be seen, reasonable agreement is obtained in only one case (NGC 7662). in the other cases, much too high values of C IV have been predicted; in NGC 7009 there is difference of at least a factor of 50.

Another method is to assume that the C IV lines are formed in regions of the same temperature as that derived from the O III lines. Since the C IV lines are formed by collisional excitation, and the temperature is known, a comparison with the Hβ flux gives the abundance of C IV. The results are shown for 5 of the 10 nebulae observed in the following table. Differences of a factor of 100 are found to exist. This is probably not an ionization effect, which is demonstrated by the fact that the ratio C^{+3}/O^{+2}, also listed in the table, varies strongly which would not be expected from ionization, since the two ions have similar ionization potentials.

It is interesting to note that there is a strong C IV line at λ4658 in NGC 2392, much stronger relative to Hβ than the same line in NGC 7027. This indicates that the lines are formed by different mechanisms. Furthermore it is clear that at present, determinations of carbon abundances are not reliable.

Nebula	$N(C^{+3})/N_H$	$N(C^{+3})/N(O^{+2})$
NGC 2392	2.6×10^{-6}	3.1×10^{-2}
NGC 3242	5.3×10^{-5}	1.6×10^{-1}
NGC 3587	3.6×10^{-6}	3.0×10^{-2}
NGC 7027	1.6×10^{-4}	8.7×10^{-1}
NGC 7662	2.2×10^{-4}	1.1

G. Central stars with A type spectra

The ANS observed 4 central stars which have been reported as A type (NGC 1514, 2346, 3132 and V-VI-7). Normal A type have also been observed with the same system. It is expected that if a hot companion were present it would be relatively much stronger in the far ultraviolet. Only in the case of NGC 1514, has a hot companion been seen, but this was already observed in ground based spectra toward λ3300 Å (Shao and Liller, 1968). The ANS observations indicate that the hot companion dominates the emission further in the ultraviolet.

For NGC 2346 there is no deviation from an A0 spectrum even at λ1550. For V-VI-7 (which may not be a planetary nebula) the ultraviolet measurements show a spectrum between A0 and A1. For NGC 3132 emission remains when an A0 spectrum is subtracted, but it can be demonstrated that this emission is due entirely to the nebular continuum and there is no evidence for a hot companion.

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DISCUSSION

Peimbert, M.: Which temperatures did you use to compute the carbon abundances from the UV CIII and CIV lines? Slightly smaller electron temperatures would yield considerably larger carbon abundances.

Pottasch: The electron temperature for each nebula was that computed from the [OIII] lines.

Forrest: Is there any hope of identifying graphite grains within planetary nebulae through their UV spectra and the 2200 Å feature?

Pottasch: The fact that the 2200 Å feature can be explained with a standard reddening curve and an E_{B-V} value which is the same as determined by Hβ to radio emission ratio indicates that if any of it is produced in the nebula, it is by the same kind of material as that producing the extinction in the interstellar medium.

Balick: Bohlin et al. (1975) have suggested that in the case of NGC 7027, photons of ground state permitted lines are resonantly scattered within the nebula and are eventually absorbed by dust. This process can be effective in reducing emergent CIV λ1550 line intensities. Has your analysis of the CIV line taken this process into account? How important do you feel this process can be?

Pottasch: In discussing the effective temperature, one should look in the infrared and see how much radiation is coming out there. In planetary nebulae the total measured infrared flux down to about 25 μ is only a small amount of the total energy used in determining the effective temperature. If there is a large amount of energy inside this region, it would be important. For example, for the central star of M8 the infrared radiation contributes about 20% of the total radiation. It's much less in planetary nebulae.

Aller: Do the ultraviolet CIII and CIV lines have an appreciable optical thickness?

Pottasch: The opitcal depth at the center of CIII is probably small, but CIV may have an appreciable optical depth ranging to more than 100 for some nebulae.

Stecher: In answer to the question about the optical thickness of the CIV line, for NGC 7027 $\tau \sim 10^4$ and for NGC 7662 $\tau = 2x10^3$. This enables one to place an upper limit on the number of absorbing grains in the nebula because multiple scattering gives such a long path length. Therefore, the dust must lie in a shell.

Dopita: Could the low intensities of the UV carbon resonance lines in fact be caused by high optical depth in the lines producing multiple scattering in the nebula? This would presumably enhance the probability of photon destruction on dust grains in the nebula.

Pottasch: It is possible that grains absorb some of the CIV radiation. I have not taken such a process into account in the analysis just presented for the following reasons. (1) There is absolutely no correlation between the strength of the CIV line (the deduced $N(C^{3+})/N(H)$) and the amount of dust (as indicated by the strength of the infrared flux). (2) There is no evidence for an increased extinction in the ultraviolet above that determined from a standard extinction curve normalized so that the correct H_{β} to radio emission ratio is obtained. In particular, the λ2200 dip is then accurately predicted.