RECENT UV AND OPTICAL OBSERVATIONS OF PLANETARY NEBULAE

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ABSTRACT. This review contains a brief survey of the issues that have been the concern of optical and ultraviolet studies of planetary nebulae since the last IAU Symposium on this subject in 1982.

The nature of this review is such that it is not possible to do justice to the wealth of work that has taken place in this period, I will just point out some characteristic examples of the different aspects of the work done.

1. ULTRAVIOLET OBSERVATIONS

The last five years have seen great advances in UV research on PN. Firstly because of the extended lifetime of IUE that has allowed the increase in the number and length of exposures allowing fainter targets to be observed, and secondly the IUE Data Bank has been steadily growing and it allows revisions of large samples of essentially homogeneous data. Other reviews on this subject are by Koppen and Aller (1987) and Perinotto (1987).

Up to now more than 130 PN have been observed in the low dispersion mode. An atlas of merged short and long wavelength spectra is being prepared by Feibelman, Oliversen and Nichols-Bolhin (1986). In most instances the aperture was centered on the PNN, although a few offset obervations have been obtained. There is also a considerable data bank of high dispersion observations that includes more than 50 PN.

1.1 Nebular Data

a) Abundances

The study of UV spectrum of PN has allowed a better understanding of the chemical composition of these objects. The UV nebular spectrum includes intercombination lines of C II], C III], N III], N IV], O IV], Si II], and Si III]; resonance lines of C II, C IV, N V, Mg I, Mg II, Si II and Si IV; as well as forbidden lines from the levels which also produce the optical lines of [N II], [O II], [O III], [Ne III], [Ne IV], [Ar III], [Ar IV], [Ar V], and [Mg V]. A number of ions can only be observed in UV, or their interpretation in terms of ionic abundances is more straightforward. Ultraviolet observations have thus made possible to derive abundances of additional elements, namely carbon which plays such a crucial role in stellar evolution, as well as of Mg and Si and improve our information on nitrogen, oxygen and neon.

The complete derivation of physical parameters and chemical abundances in the nebulae are usually carried out by optical spectrophotometry in conjunction with IUE spectra and very often are supplemented with model ionization structures that allow for unobserved ionic stages; normally from

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the stellar UV continuum and nebular line ratios an improved value of the interstellar reddening is also derived. UV data limit the possible nebular models since more severe constraints on physical processes, excitation conditions, and stellar fluxes below 912 A can be set.

Usually IUE spectra have been acquired for individual objects that have been investigated in detail for abundance determinations. Aller and Czyzak (1983) presented extensive optical observations for 41 PN and used available IUE data for one third of their objects. They derived C, N, O, Ne, S, Cl, and Ar values whenever possible. In a recent compilation, Zuckerman and Aller (1986) list C, N, O, Ne, Ar, and S abundances for 44 nebulae, where most have C abundances derived from IUE data.

The same analysis can be carried out for extragalactic planetary nebulae. Maran *et al.* (1982) performed UV observations on 3 high excitation PN in the Magellanic Clouds, (LMC P40, SMC N2, and SMC N5) and determined their chemical abundance where they found that C is greatly enhanced relative to the interstellar medium. Maran *et al.* (1984) observed the only known PN in the Fornax galaxy, probably the most distant PN that can be observed with IUE. They combined it with optical data and found that it resembles the three PN in the Magellanic Clouds; it is deficient in N, O, Ne, S and Ar, but not in C, relative to the planetaries in the Milky Way.

b) Physical Processes

IUE observations have also given the opportunity to carry out a more thorough examination of physical processes, in particular dielectronic recombinantion, and charge exchange processes whose effects are more pronounced in the UV. For example, Clegg, Harrington and Storey (1986) reported the detection of the 2600 A triplet and quintet Ne III lines from high dispersion spectra in NGC 3918 produced by charge transfer reactions between Ne^{3+} and H^{o}.

1.2 Data on Central Stars

a) Stellar Parameters

For most of the planetary nebulae nuclei (PNN) observed in the optical range only the Rayleigh-Jeans tail of the energy distribution can be detected. The extension of the stellar continuum and line spectrum to shorter wavelengths improves considerably our understanding of the nature of hot stellar atmospheres. Traditional optical spectroscopy for determining stellar temperatures can be improved with IUE data. The Zanstra method can be applied to the stronger stellar continuum and the brighter He II 1640 A line.

Kaler and Feibelman (1985) analized the spectra of the central stars of 32 extended PN (larger than 0.2 pc). From ultraviolet and UV- to-optical flux ratios they derived color temperatures. Their values of the color temperatures are far in excess to those derived from the Zanstra method. They found that in general, the stars where the continuum contribution is indistinguishable from a Rayleigh-Jeans distribution have lower intrinsic luminosities.

b) Stellar Wind Properties

Although it had been known that PNN of the W-R type have expanding atmospheres, definite proof of mass loss in PNN was presented only through observations of P Cygni profiles in UV lines (Heap *et al.* 1978). The great breadth of their P Cygni lines permit fast winds to be recognized even in the low spectral resolution mode. PNN show these mass loss manifestations mainly in the resonance lines of N V, Si IV, and C IV. The edge velocities in these lines are of the order 1000 to 3000 km s^{-1}. Little is known about the ionization mechanisms and stratification in the winds.

Mass loss rates for these winds have been determined from fitting high dispersion spectra of NGC 1535 (Adam and Koppen 1985). Cerruti- Sola and Perinotto (1985) analyzed low dispersion IUE

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spectra of 60 central stars; they found that 22 out of 42 spectra with recognizable stellar continuum display P-Cygni profiles. All low excitation PN (without nebular He II) have winds but for some high excitation PN no wind has been detected. Cerruti-Sola and Perinotto were able to determine that for PNN with surface gravity less than about log g = 5.2, there is strong mass loss present in the star. They determined mass loss rates in the 10^{-10} to 10^{-7} $M_{\odot}$/yr range.

2. OPTICAL OBSERVATIONS

We have seen during this period both the increase in number of scientists devoting their energy to the research of PN as well as widespread operation of better instrumentation. In general it can be said that there are more data, better quality measurements and new observational and data reduction techniques that have broadened our scope.

The major instrumentation advances for optical studies have dramatically affected the subject; very sensitive 2-dimensional detectors have given us a more detailed picture of structure of the PN as well as spatial information on line intensities and velocity fields.

2.1 Search for New Objects

The discovery of new PN continues to take place. At present the number of identified galactic PN is of about 1600 objects; for comparison it should be pointed out that the number of entries in Perek and Kohoutek's (1969) catalogue is of 1067. Most of the discovery work is done in optical wavelengths.

In our galaxy we know only about 10% of all PN, and the rest are heavily reddened. The northern sky has been carefully searched on different sets of material, the southern sky has not been studied so thoroughly, nevertheless new objects are still being found in both hemispheres. For example, Hartl and Tritton (1985) reported 14 new objects from deep J and R plates taken at the UK 1.2-m Schmidt telescope and Shaw and Wirth (1985) reported 7 new PN in Baade's window, while Ellis, Grayson and Bond (1984) report 6 new possible PN from a new revision of the Palomar Survey prints.

As is to be expected, there has been a dramatic increase in the identification of new extragalactic PN. Morgan (1984) classified 134 PN in the Magellanic Clouds and estimated [O II]/Hβ ratios for 29 nebulae in the SMC and 85 in the LMC. Morgan and Good (1985) reported 10 new possible PN in the SMC. Meysonnier, Azzopardi and Lequeux (1988) reported a survey covering 2/3 of M31 and found about 1200 objects showing emission lines between 4350 and 5300 A, believed to be PN.

2.2 Nebular Research

a) Direct Imaging

The possibility of obtaining deep CCD images of PN has allowed the search of faint extended nebulosities beyond the dense nebulae. Jewitt, Danielson, and Kupferman (1986) from CCD images in Hα of 44 objects of 10 to 100" diameter found halos previously undetected in 29 of them; many of the halos exhibit filamentary structure; they also determined that their masses are comparable to the masses of the denser shells.

Chu, Jacoby, and Arendt (1987) from direct images through narrow band filters plus available data, found that the frequency of multiple shell events is larger than 50%. Balick (1987) from direct images of 51 PN in the light of Hα, [O III], [N II], He II, and [O I] defined 3 morphological categories: 'round', 'elliptical' and 'butterfly'. He proposed that nearly all PN fall in these general categories suggesting a common history.

Also the possibility of direct imaging through narrow band filters has allowed detailed studies to determine temperature, density and ionization structures of extended PN. Images in the light of Hα, [N II], [O II], [O III], [S II], in NGC 40 and NGC 6826 were obtained by Jacoby, Quigley and Africano (1987), from these data they derived detailed physical conditions and ionic abundances at each position.

b) Speckle Interferometry

Wood, Bessell and Dopita (1986) have obtained speckle interferometry in the light of [O III] 5007 A and have derived angular diameters of Magellanic Clouds PN (two objects in the SMC and nine objects in the LMC). The mass of ionized gas is derived in each nebula from the angular diameter and published Hβ line fluxes; the derived masses range from 0.005 to 0.19 $M_{\odot}$ with a mean value of 0.08 $M_{\odot}$; all the PN observed are the brightest objects in the clouds. They concluded that the nebulae are most certainly partially ionized, and that the masses derived at the ionized part of the nebulae are lower limits to the total nebular mass. Barlow *et al.* (1986) obtained speckle interferometry in [O III] of N2 in SMC; they found the nebula to be distributed in two shells, an inner one of 0.22" and an outer one of 0.38", which correspond to sizes of 0.06 and 0.10 pc, and to masses of 0.09 and 0.27 $M_{\odot}$, respectively.

c) Spectrophotometry

The accumulation of high quality line intensities has allowed detailed analysis of nebular parameters for a large number of individual PN. This work has been coupled with ionization structure models. It has been possible to determine the He, C, N, O, S, Ar, Cl, and Mg abundances relative to H for large number of objects. This research has been pursued by many authors that have carried out detailed analysis of individual nebulae (see references in compilation by Zuckerman and Aller 1986). Abundaces for a large number of objects have been determined by Aller and Keyes (1987) for 51 objects, by Aller and Czyzak (1983) for 41 objects, by Kaler (1985) for 12 nebulae, and by Peimbert and Torres-Peimbert (1987) for 16 PN of Type I. It is of interest to note that Acker and Koppen (1988) present a paper in this Symposium where they report to have obtained homogeneous spectrophotometric data for 900 PN.

It has also been possible to derive chemical abundances of PN in other galaxies. Jacoby and Ford (1986) analyzed 3 PN in M31. Spectrophotometry of PN is at present the only means of measuring chemical abundances in individual stars at the distance of M31. The oxygen abundances in a disk PN and in an H II region appear to be higher in the disk of M31 than in the disk of the Galaxy. They also found from the abundance of 2 of the PN, which are halo objects and which have different O/H ratio, that the halo of M31 is chemically inhomogeneous. Monk, Barlow and Clegg (1988) have derived chemical abundances for 71 PN in the Magellanic Clouds.

Barlow (1987) studied PN in the SMC and LMC; he derived the electron density from [O II] 3727/3729 and from Hβ determined their mass. In 18 PN of the SMC he derived a nebular mass of 0.02 to 0.45 $M_{\odot}$; in his sample, he found Type I objects, that is, PN with $N/O > 1$. In 14 objects in the LMC he derived nebular masses from 0.0076 to 0.69 $M_{\odot}$.

d) Radial Velocity Measurements

The number of PN for which there are available radial velocity determinations is large; for example,the catalogue by Schneider *et al.* (1983) comprises 524 objects; it lists 287 objects, with an accuracy better than 10 km s^{-1}. Most of this work has been done in the optical lines.

e) Nebular Kinematics

Many individual nebulae have been studied in detail through Fabry-Perot interferometry, high dispersion coude and echelle spectroscopy. The increase in data has been considerable, and more details of their velocity fields are known about them.

The catalogue of expansion motions by Sabbadin (1984) comprises 165 objects; an updated compilation is being prepared by Weinberger (1988). From a comparison of expansion velocity *vs.* linear size, Sabbadin concludes that there are systematic differences between planetary nebulae of class C and B morphological types of Greig (1971), and that the expansion models are consistent with the class C objects having been ejected and excited by post asymptotic giant branch stars having a final mass $\sim$ 0.60 $M_\odot$, and a nebular mass $\sim$ 0.20 $M_\odot$, while the class B objects having been ejected and excited by central stars of final mass $>$ 0.60 $M_\odot$ and nebular mass from 0.3 to 1.0 $M_\odot$.

Anomalies in the expansion motions of nebular material have been found. High velocity jet-like bipolar mass flow in NGC 2392 have been found from high dispersion Hα and [N II] images; the flows are of 200 km s^{-1} (O'Dell and Ball 1985; Gieseking, Becker, and Solf 1985). Walsh and Meaburn (1987) studied the Helix Nebula, NGC 7293, and found a faint external filament that shows a radial velocity of 50 km s^{-1}, as compared to 25 km s^{-1} in the bulk of the nebula; they attributed it to an ionized remnant of an early ejection event of the central star, where the high velocity expansion is an indicator of a superwind stage. Reay and Atherton (1985) have determined the kinematics of NGC 7009 from observations at [O I] 6300 A; they found condensations symmetrically disposed in velocity about the central star.

High expansion velocities have been found in extragalactic objects as well; for example, in a few PN of the LMC expansion velocities of 100 km s^{-1} have been observed (Dopita, Ford and Webster 1985).

2.3 Data on Central Stars of PN

a) Magnitudes of Central Stars

Walton *et al.* (1986) obtained narrow band continuum CCD images of 21 PN where the central stars had been poorly dectected or undetected (of magnitude fainter than 14). They were able to measure the visual magnitude of the central stars in 19 of them. Three objects in the sample have temperature greater than 2×10^5 K (NGC 3918, NGC 3211, and NGC 2440); their position in the H-R diagram can be explained if they have masses greater than 0.8 $M_\odot$. This technique is particularly useful for those nebulae whose central stars are faint or below the visual threshold.

b) Variability of Central Stars

Studies of photometric variability of PNN have established the presence of close binary systems not previously known. For example, Grauer *et al.* (1987) reported the discovery of sinusoidal variations with a 13.96 hr period and amplitude of 1.1 mag in the B band of the central star of HFG1. Reviews on the presently available data on binary systems are given by Bond (1988) and Mendez (1988).

Observational evidence was presented for the first time that shows the central star of a PN to be a pulsating variable (Grauer and Bond 1984). K1-16 has a main period of 28.3 min with a semiamplitude of about 0.01 mag. Spectroscopically and photometrically, the central star of K1-16 closely resembles the previously known hot pulsator PG 1159- 035; these two objects exhibit a new pulsational instabilty mechanism for extremely hot degenerate or predegenerate stars. It demonstrates pulsational instability present in a new region of the H-R diagram and provides an opportunity of direct observation of stellar evolution.

c) Temperatures and Gravities

There has been a considerable effort to derive more dependable physical parameters of PNN. Mendez *et al.* (1985, 1987) from spectroscopic data of central stars, and by fitting stellar H and He absorption lines with theoretical profiles, have been able to derive accurate stellar temperatures (± 5000 K), log g values (± 0.2 dex), and photospheric He/H ratios (± 0.02) for a sample of 28 objects.

3. CONCLUSIONS

The advances in observational material for the study of PN have been outstanding. High quality data have been secured for an increasing number of objects, including the fainter ones.

Our understanding of the properties of the central stars has increased. Stellar winds, magnitudes and colors have been measured from observations; also effective temperatures and gravities have been derived. It will be very important to determine stellar wind characteristics on different positions of the H-R diagram.

Our knowledge on the nebular parameters has improved; especially in the abundance determinations, kinematics and morphology. Increased attention is being paid to morphology and kinematics since it is hoped that thet can help us to a better understanding of the ejection mechanisms of the nebulae.

Ultraviolet work on the objects will depend on the continued operation of IUE and on the succesful launch of the Space Telescope. Optical work on fainter objects and of higher angular resolution from larger telescopes that are under construction will be possible.

The Space Telescope operation will allow for better studies of Magellanic Clouds PN, where nebular sizes, masses, chemical composition, and central stars magnitudes and colors will allow direct comparison of evolutionary tracks with observations.

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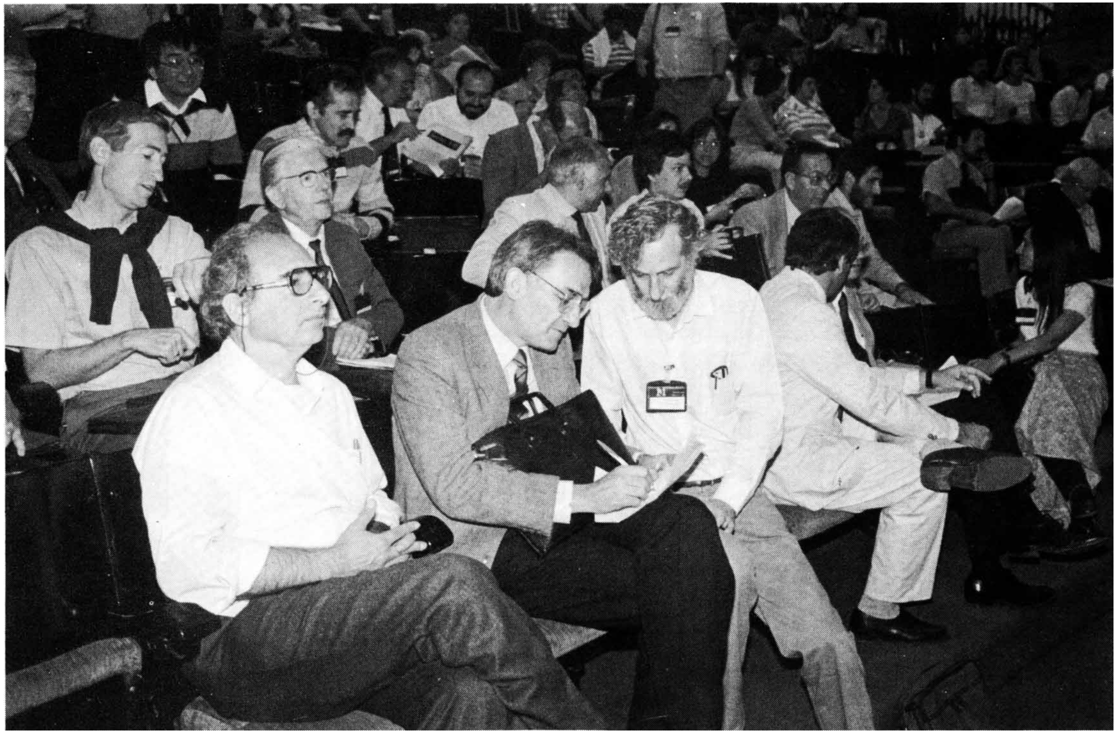

First Row: Stuart Pottasch, Manuel Peimbert and Michael Feast. Second Row: Detlef Schönberner and Volker Weidemann.

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