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Observational studies of planetary nebulae with moderate-size telescopes

D.C.V. Mallik

Indian Institute of Astrophysics, Bangalore 560034, India

Abstract. Planetary nebulae represent an important phase in the evolution of the vast majority of stars in a galaxy. They are easily recognised because of their characteristic emission-line spectra. The small ones can be seen at large distances because of their high surface brightness. These properties make them wonderful laboratories to study atomic physics, chemical and dynamical properties of galaxies and of course, the evolution of low-and intermediate-mass stars. The fundamental parameters of the nebulae are their distances, chemical composition, the luminosities and temperatures of their nuclei. Moderate-size optical telescopes equipped with appropriate focal plane instruments have succeeded in creating a massive observational database for these nebulae. Ultraviolet and infrared observations have complemented these groundbased efforts.

Some of the important observational aspects of the studies of these nebulae are discussed. The emphasis is on the discovery aspects, on the diagnostic aspects that lead to a determination of the properties of the nebulae and most importantly, on the measurement of distances to the nebulae and their nuclei.

1. Introduction

Ignition of carbon in a degenerate core leads to catastrophic consequences in the life of a star and although there is no law of nature that says it should not happen, there are enough observational indications to suggest that this does not happen. All stars of main sequence masses $m \leq 7 \pm 1\ M_\odot$ develop degenerate C + O cores following the cessation of He burning in the core and further core contraction. Since the pioneering study by Deutsch (1956) of the α Her system, enormous amount of evidence has accumulated to indicate that all evolved stars lose mass. The region of the H-R diagram populated by mass losing stars (e.g. Mira variables, OH/IR stars, carbon stars) is the region where post main sequence evolutionary tracks of low- and intermediate-mass stars converge beyond core He burning when the stars are in a thermally pulsing double-shell-source phase (TP-AGB). Stars in this region have huge circumstellar envelopes which are detected in a variety of ways and they lose mass at rates anywhere between $10^{-5} - 10^{-9}\ M_\odot\ \mathrm{yr}^{-1}$.

The first spectrum of a planetary nebula was taken by William Huggins in 1864 who discovered the unusual spectral appearance of these objects; in the blue-green region there were only a handful of emission-lines, Hβ at 4861 Å, the green nebular lines at 4959 Å, 5007 Å and a line at 3727 Å. Another important observational fact to be discovered about these nebulae was that all of them were observed to be expanding with typical velocities in the range of 10-30 km s^{-1}. The low expansion velocities indicate that the nebulae could not have been ejected by the compact blue nuclei which power them. On the other hand, escape velocities of stars on the upper right corner of the H-R diagram are low. The structure of a TP-AGB star is strikingly similar to the structure of a planetary nebula with the core of the star resembling the blue compact nucleus and the envelope an earlier evolutionary version of the nebular shell. These similarities in structure and equality of velocities led Shklovsky (1956) to advance the hypothesis that red giants are the precursors of planetary nebulae. In today's terms we shall change the wording only marginally by replacing *Red giants* by TP-AGB stars. The loss of mass and the loss of the enormous envelopes from these evolved stars ensure that the remnant core never reaches the point of carbon ignition, nor grows to the magical value of 1.4 $M_\odot$.

The planetary nebula phenomenon is thus very common. If we assume that our solar neighbourhood sample of these nebulae is complete, the number of nebulae per unit mass can be derived, a quantity called the specific number κ. For several popular estimates of σ and Σ, respectively the surface density of nebulae by number and the total surface mass density,

$$\kappa = \frac{\sigma\ (pc^{-2})}{S(M_\odot\ pc^{-2})} = 1.6 \times 10^{-7} M_\odot^{-1}$$

If we then assume that this number holds anywhere in the Galaxy, the total number of nebulae in the Galaxy $N = \kappa m_G \sim 30{,}000$. This number is correct to a factor of two.

As the nebulae expand they become faint - a property of any fully ionized shell since the surface brightness $S \propto R^{-5}$. Beyond a certain size, therefore, it is nearly impossible to detect a planetary nebula through imaging. Setting 1 pc as a cut-off limit for the visible nebulae and $V_{exp} = 20\ km\ s^{-1}$, we derive an age $t = 5 \times 10^4$ yr. The Galactic birthrate: $N = 0.6$ yr^{-1} and since $T_{Gal} = 15$ Gyr we estimate about 10^{10} objects have gone through the planetary nebula phase. The Galactic turn-off mass being about 0.85 $M_\odot$ and the number of stars above this mass being about 10% of the total (Salpeter IMF), the number of evolved stars in the Galaxy is about 10^{10}. Continuous star formation would perhaps affect this result by a factor of two.

Thus *almost all stars in the Galaxy have evolved through the planetary nebula phase.*

Today more than 1300 planetary nebulae are known in our Galaxy and these have been catalogued in the Strasbourg - ESO Catalogue (Acker et al. 1992). There may be more waiting to be discovered but interstellar extinction poses severe problems for optical identification of these. The large ones are missed because of their low surface brightness.

2. Discovery and confirmation

Traditionally, planetary nebulae (PN) were discovered on careful examination of Palomar Observatory Sky Survey (POSS) plates. The detection limit, assuming the limiting surface brightness in V to be $25.^m0$ arcsec^{-2} translates to an EM = 31 cm^{-6} pc and therefore a limiting $n_p \sim 6$ cm^{-3}. Many low-density planetaries may be close to the detection limit. Recent examination of this problem by Ishida and Weinberger (1987) and Tamura and Weinberger (1995) indicates that Abell who did the initial survey in 1966 missed about half of the fainter nebulae on POSS. Today, there are better methods of searching POSS plates and there have been other Schmidt surveys. Many new planetary nebulae have been detected. More than 500 objects have been added to the list since the publication of the PK catalogue (Perek and Kohoutek 1967) and they have all been included in the Strasbourg-ESO Catalogue (hereafter CGPN). There are several misclassified PN in this list and one of the first uses of a telescope with PN programmes on it is to confirm the identification of these objects.

To confirm that these are PN optical spectroscopy needs to be done, for there is no better way of confirming a PN than (a) measuring the relative [OIII] $\lambda 5007/H\beta$ flux, (b) detecting expansion in either [OIII] or $H\alpha$ or $H\beta$ lines through Fabry-Perot spectroscopy, and (c) measuring diagnostics like [S II] λ 6717/λ 6731 for electron density estimates.

An extensive long-range programme along these lines has been running at ESO and at the Haute-Provence Observatory, France.

The ESO 1.5 telescope with a B&C spectrograph and an Image Dissector Scanner and the Haute-Provence (OHP) 1.93 m telescope with the CARELEC spectrograph and a CCD detector are used for this purpose. The telescope-detector arrangement is displayed in Table 1. It is particularly advantageous to use these methods on small compact nebulae. The extended low surface brightness ones are difficult to observe this way. About 20% of the objects in CGPN are perhaps not PN. Symbiotic stars, HII regions, galaxies, reflection nebulosities, SNR knots comprise these objects.

Table 1. Instrument configurations.

	European Southern Observatory (ESO)	Observatoire Haute Provence (OHP)
Telescope	1.52m	1.93m
Spectrograph	Boller & Chivens	CARELEC
Detector	IDS, currently CCD	CCD
Number of useful pixels	2053	511
Aperture	4"x4"	2".5x3"
Appr. wavelength range	4000-7400Å	3850-7400Å
Dispersion	170 Å/mm	260 Å/mm
Appr. resolution	10 Å	20 Å
Normal exposure time	10 min	10 min

For the extended nebulae Weinberger and group have used a scanning Fabry-Perot spectrometer at the 1.23 m telescope on Calar Alto, Spain. The spectral resolution is about 10 km s^{-1} in [OIII] and 12 km s^{-1} in $H\alpha$ and [N II]. An RCA photomultiplier tube was used as the detector and line profiles were produced. The observed nebulae are several arcminutes in diameter. Scans were taken at the centre of the nebulae so that from direct line-widths or line-splittings V_{exp} could be measured:

$$2\,V_{\mathrm{exp}} = [FWHM^{2}_{obs} - FWHM^{2}_{instr} - FWHM^{2}_{th}]^{1/2}$$

The PRL Fabry-Perot spectrometer has been used at the 1-m Zeiss telescope in Kavalur to measure expansion velocities of a dozen or more nebulae (Sahu 1985, Banerjee et al 1990).

Much of the recent studies of new planetary nebulae are based on the IRAS survey. All planetary nebulae, especially the younger ones, are strong infrared emitters as the shells contain dust formed in the cool extended atmospheres of the precursor stars. They occupy a unique area in the IRAS two-colour diagram that plots: 2.5 log $(F_{60\mu}/F_{25\mu}) \equiv [25] - [60]$ against 2.5 log $(F_{25\mu}/F_{12\mu}) \equiv [12] - [25]$ (Fig. 1). The dust emitting temperature of the nebulae is between 100 and 300 K. As can be seen in the figure, the region occupied by the nebulae is not contaminated by galaxies (barring a few Seyferts), H II regions or normal stars. The unidentified sources with PN-like colours are probably young PN since these are distributed in the plane and the spatial distribution shows concentration to the Galactic Centre and the Bulge region, very similar to the distribution of known optically identified PN. To confirm the nature of these objects a multiwavelength strategy is usually adopted and again optical spectroscopy plays a prominent role. However, many of these objects may be either totally optically obscured or are so faint that only 4-m class telescopes can handle their discovery. For the totally obscured ones high-frequency radio observations are necessary to confirm the thermal nature of their spectrum. Confusion with compact HII regions is a potential source of problem. For the others, groundbased 10μ measurements for better positional information, near IR photometry, spectroscopy in the

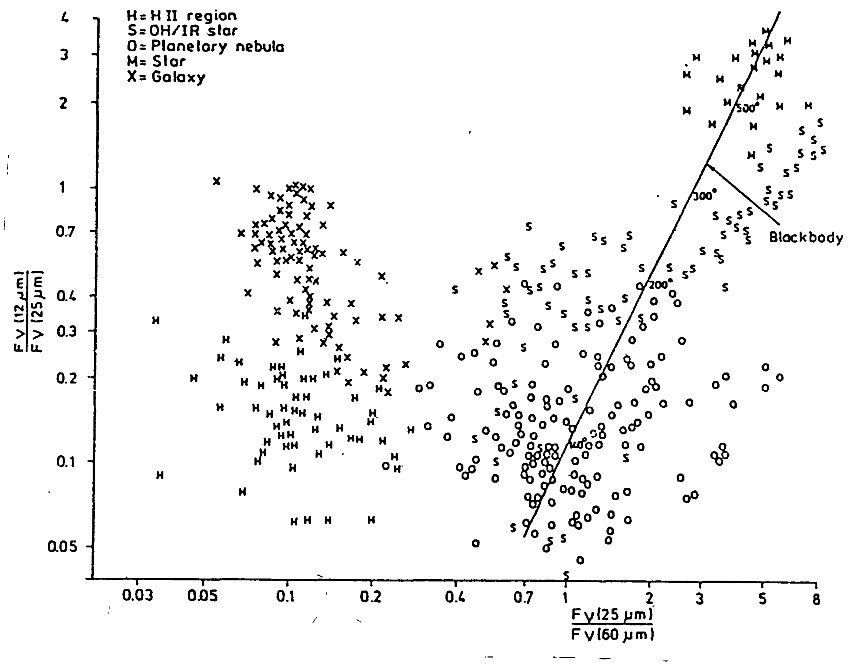

Figure 1. Color-color plot of the IRAS fluxes of various known astronomical objects. The planetary nebulae are found in a region of the diagram separate from most other objects, except for some of the OH IR stars. (Reprinted by permission, from A&A, 205, 248, 1988. Copyright (1988) European Southern Observatory).

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visible, wherever possible, are done. In this way several tens of new PN are discovered. The Infrared Space Observatory (ISO) which has done systematic spectroscopy of these objects is likely to confirm the objects as PN from the infrared line diagnostics (Pottasch 1996).

3. Parameters for the central stars

As stated before, each nebula is powered by a blue compact nucleus and in the majority of the cases the nucleus is clearly seen in an image of the nebula. This star is evolving towards the white dwarf phase with still some nuclear fuel left in the form of a H- and/or He- burning shell. It is bright compared to a normal white dwarf.

The major preoccupation in planetary nebula research in the last couple of decades of has been to place this star accurately on the H-R diagram. To do this we need to know two quantities: the luminosity L of the star and its effective temperature T_s. It is difficult to know L without a determination of T_s since for these very hot stars the bolometric correction may be substantial and just the knowledge of m_v and the distance is not enough.

The three fundamental observational quantities are thus (a) the distance to the nebula or its central star (CSPN), (b) the visual magnitude of the star and (c) the temperature of the star.

In each of these areas telescopes of apertures between 1 and 2 m have been used very effectively.

Distances

Distances to planetary nebulae are difficult to estimate as the regular method of spectroscopic parallaxes is inapplicable and very few nebulae are near enough to have measured trignometric parallax etc. Of the various methods that have been devised to obtain distances some need large telescopes, some need complementary radio observations. A moderate-size optical telescope may be used in some of these methods to great advantage.

Direct methods

1. Extinction or dust distances:

Spectral type and B and V magnitudes of field stars in line of sight to the nebula are measured by standard methods of CCD photometry and low-resolution spectroscopy. Spectroscopic parallaxes are used to produce a E(B–V) vs m–M diagram of the field objects. E(B–V) of the nebula comes from an independent measurement: (a) the Balmer decrement Hα/Hβ, or (b) comparing intrinsic F(Hβ) inferred from 5 GHz radiocontinuum measurement with the observed F(Hβ) or (c) dereddening of the uv continuum of the star observed with IUE containing the 2200 Å interstellar absorption feature.

The distance modulus of the PN/CSPN is directly read off the diagram. This method has been employed for dozens of nebulae starting with Lutz (1973) followed by the most extensive work of Gathier (1984) and continuing to the present time.

Patchiness of ISM, accurate calibration of two-dimensional classification of spectra to derive M_v, accurate classification of the spectra themselves are potential problems.

2. Expansion distances:

From VLA maps angular expansion may be measured and if nebular expansion in km s^{-1} is measured by optical spectroscopy

$$d(pc) = 100(\frac{V_{exp}}{kms^{-1}})/4.74\ (\frac{\dot{\theta}}{arcsec\ per\ century}).$$

About a dozen nebulae have been thus measured with a 6 year baseline using the cross-calibration technique pioneered by Masson (1989). Measured expansions are in the range of a few milliarcsecond yr^{-1}.

HST is expected to measure expansions over a 10-yr baseline.

3. Spectroscopic parallaxes:

A small fraction of central stars e.g. NGC 246, NGC 1514, NGC 2346, NGC 3132 are members of binary systems. If the companion were a normal main sequence star or giant whose spectral type is accurately known, the method of spectroscopic parallax applied to it leads to an estimate of the distance to the CSPN and hence the PN itself.

Indirect methods

These fall into two categories depending on the physical state of the nebula:

(a) for nebulae that are optically thick in the Lyman continuum, we have the constant flux method, and

(b) for nebulae that are fully ionized or optically thin in the Lyman continuum, we have the constant mass method.

Constant flux method

All ionizing photons are absorbed and in equilibrium

$$4\pi R_*^2 \int_{\nu_o}^{\infty} \frac{\pi F\nu}{h\nu} d\nu = \frac{4}{3}\pi R^3 n_e n_p \alpha_B(T) = Q .$$

The observed flux $\pi F(H\beta) = \frac{4/3\ \pi R^3 n_e n_p \alpha_{H\beta}(T)}{4\pi D^2} = Q\frac{\alpha_{H\beta}}{\alpha_\beta}\frac{1}{4\pi D^2}$

Thus $D^2\pi F(H\beta)$ = constant, since Q is constant along an evolutionary track.

This relation may be calibrated with nebulae whose distances are known directly. Measurement of $\pi F(H\beta)$ yields D. For optically obscured nebulae 5 GHz radioflux may be used since $F_{5GHz}/F(H\beta)$ is only a function of the electron temperature T_e $\pi F(H\beta)$ may be obtained and hence D.

Constant mass method

When the nebular shell is fully ionized $4/3\pi R^3 n_p m_H f = M$, f being a number that takes care of He ionization.

Thus $n_p R^3$ = constant if all shells have about the same mass.

The surface brightness $S\beta = \frac{\pi F(H\beta)}{\phi^2} = const.R^{-5}$

Calibration of this relation yields the constant which involves the mass M.

Then $\pi F(H\beta)$ and ϕ or F_{5GHz} and ϕ yields R and hence $D = R/\phi$.

Both these methods require measurement of $\pi F(H\beta)$ and of course, of E(B–V) to yield the true $H\beta$ flux. A large effort has therefore been expended to obtain accurate $H\beta$ fluxes and extinction constants of large samples of PN. The $H\beta$ flux is measured by the standard methods of photoelectric photometry. Almost the first set of such measurements was made by Collins et al. (1961) and O'Dell (1962) using the Whitford-Code photoelectric spectrum scanner at the 90 cm telescope at Pine Bluff Observatory, USA. More recently, a much larger programme of measuring Hβ fluxes and the extinction has been included in the ESO/OHP PN spectroscopy project mentioned in Section 2. Accurate spectra of close to a thousand planetaries belonging to CGPN have been obtained and used to estimate the above quantities (Acker et al. 1989; Acker et al. 1991; Tylenda et al. 1992).

The apertures used are compatible with the sizes of the smaller nebulae ~ a few arcsec and the fluxes are accurate to 0.07 in dex. For the more extended nebulae only a part of the light goes through and the measured fluxes have to be corrected upward to obtain total Hβ fluxes of the nebulae. This degrades the accuracy to about 0.3 in dex. Thus the method is really suited to compact nebulae i.e those with diameters less than ~ 5".

A related measurement is that of the extinction. Since spectra are obtained the Balmer decrement method is usually the most convenient one to use.

$$\left[\frac{\pi F(H\alpha)}{\pi F(H\beta)}\right]_{obs} = \left[\frac{\pi F(H\alpha)}{\pi F(H\beta)}\right]_{intrinsic} e^{-C[f(H\alpha)-f(H\beta)]}$$

where f(λ) is the standard interstellar extinction curve.

The constant C or log c = 0.434 C can be determined. Extinction varies over a huge range from a few hundredths in C to about 2 or 3 for the most heavily reddened objects. The dust optical depth $\tau_\lambda = Cf(\lambda)$.

Some years ago we proposed a new distance scale of planetary nebulae based on the idea of a constant $H\beta$ luminosity (Mallik and Peimbert 1988). The scale was calibrated with the measured $H\beta$ fluxes and radiocontinuum fluxes of 36 or so nebulae for which direct methods yielded distances. The result $<E(H\beta)> = 3.50 \text{ x } 10^{34}\ erg\ s^{-1}$ which was then inverted to yield $D(pc) = 0.0171[\pi F(H\beta)]^{-1/2}$.

We then considered a sample of Galactic Centre PN (30 objects) with measured 6 cm radio continuum fluxes. These were converted to $\pi F(H\beta)$ to yield

$$< \pi F(H\beta) > = 5 \times 28 \times 10^{-12}\ erg\ cm^{-2}\ sec^{-1}.$$

From this we obtained $D_{GC} = 7.44$ kpc which is to be compared to the standard value 7.8 kpc.

Absolute $H\beta$ fluxes have also been measured by Kaler and his collaborators by photoelectric filter photometry using the 1-m telescope of the University of Illinois at the Prairie Observatory. Specially made interference filters were used to observe emission lines and the continuum. The photometer has a maximum aperture of 7' so that absolute fluxes could be measured for almost any planetary nebula. The telescope at the cassegrain focus can work at either f/7.6 or f/13.5 mode. These measurements coupled with recent radiocontinuum measurements form the catalogue by Cahn, Kaler and Stanghellini (1992) which is an updated version of the Cahn and Kaler catalogue (1971).

Magnitudes of central stars

In addition to distances, magnitudes of central stars and their temperatures are the other important parameters.

Although a photelectric magnitude measurement may be the simplest of measurements in optical astronomy, the case of CSPN is slightly complicated since the star sits in the middle of a nebula which has its own continuum emission. The nebula often has structure on subarcsecond scales and the star itself being hot is faint in the visible while the nebular continuum gets brighter with increasing T_s. Accurate magnitude estimates are thus of relatively recent origin.

For those nebulae where the star is clearly seen and the nebula is large and contamination due to nebular continuum is small V band CCD photometry on any moderate size telescope yields accurate magnitude measurements.

When these conditions are not satisfied something more sophisticated has to be done. One way is to go to the ultraviolet since the star surely gets brighter and the nebula weaker. This with the diffraction-limited performance of HST is today yielding the most accurate magnitude measurements of CSPN.

With the groundbased telescopes a 'nebular subtraction technique' is generally used. A map of the nebula is made in an emission line, say $H\beta$. Since $\pi F(H\beta) \infty n_e n_p f(T_e)$ and $\pi F_{nebcont} \infty n_e n_p f'(T_e)$, the line map can be used to generate a nebular continuum map at any appropriate wavelength. Next a continuum map of the nebula and the star is obtained in a narrow band away from the emission lines. A subtraction of the former map from the latter yields the narrow band magnitude of the star. First applied by Jacoby in 1988 to detect unambiguously the central star of NGC 7027, the technique has had singular success in the measurement of magnitudes of a dozen or so important well studied PN for which the nuclei were never seen earlier. Many of these of course have now been revealed in HST images. The nucleus of NGC 6302 is still unseen.

The dust distribution, both foreground and internal, can also be studied in a similar fashion. A radiocontinuum map can translate to an intrinsic Hβ map of the nebula and an observed Hβ map of the nebula may then be compared to obtain τ(Hβ) on the face of the nebula and hence the extinction A(Hβ) can be determined.

4. Conclusion

I have tried to indicate some common areas of work in planetary nebula studies where moderate-size telescopes have been extensively used with great success. Lots of work can be done with these telescopes once they are equipped with state-of-the-art focal plane instruments. In addition, there are specialised problems in nebular studies where one needs high-resolution high signal-to-noise spectra to study problems of radiation transfer, to detect neutral circumnebular envelopes etc. These can surely be attempted with a 3-m size telescope.

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