MORPHOLOGY AND KINEMATICS OF PLANETARY NEBULAE

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The application of monochromatic images and internal kinematic data to the construction of 3-dimensional models for the HII regions of planetary nebulae is discussed, and the role of models in investigating envelope evolution is commented upon.

The quality and usefullness of available data is critically reviewed, and examples of 'seeing limited' kinematic and isophotometric data obtained with a new imaging Fabry-Perot system are presented.

INTRODUCTION

The remarkable variation in the appearance of different planetary nebulae has led to interpretations in terms of spherical, elliptical, cylindrical, toroidal and helical density distributions, often with double and sometimes triple shells comprising combinations of one or more of the above 3-dimensional shapes. In addition, knots, filaments, ansae and stratification effects contribute to produce a very large variety of nebular forms.

Since planetary nebulae appear to constitute a physically related class of astronomical object, however, their spatial forms must be governed by similar dynamical forces, and they should be expected to have similar or related intrinsic forms. The diversity of observed shapes must be the result of a range of conditions at the point of nebular ejection and/or evolution of the nebula after ejection, coupled with stratification effects and projection effects onto the plane of the sky.

If we accept this statement to be true, then in principle geometric modelling of a sufficiently large sample of planetary envelopes will give a clearer view of the range of intrinsic 3-dimensional structures, and when specific geometries are used in conjunction with ionisation models, a more complete understanding of the physical processes at work in the shell.

D. R. Flower (ed.), Planetary Nebulae, 31–43.

Modelling will also enable us to investigate evolutionary links between different nebular geometries and, possibly, to comment on conditions prevailing on the surface of the progenitor at the time of envelope ejection.

To make progress in this direction it will be necessary to model a large number of nebulae (60 or more), chosen as representative examples of known visual forms, and for each nebula we will require a uniform data set comprising

(a) Photometrically calibrated monochromatic images in Hα or Hβ and a number of other lines covering a range of ionisation potentials e.g. [OI] 6300Å, [OII] 3727/29Å, [OIII] 4363Å and 5007Å, [NII] 6584Å, [SII] 6717/31Å, [NeV] 3426Å and HeII 4686Å.

(b) Velocity field information at 'seeing limited' spatial resolution over the envelope, and at a spectral resolution of 50,000 ($\sim$ 6 km s^{-1}).

In the following I review briefly the data currently available, commenting on its scope and limitations and the way it has been used to deduce the 3-dimensional structure of planetary envelopes. Finally I will discuss methods currently employed by my colleagues and I to obtain data in catagories (a) and (b) above, in order to establish a uniform morphological and kinematic data base for a large sample of planetary nebulae.

OBSERVATIONS AND MODELLING

Studies of the distribution of emission intensities in planetary nebulae, usually photographically, are too numerous to cite individually. References to past literature are contained in the proceedings of the two planetary nebulae symposia IAU 34 (1968) and IAU 76 (1978). Much, although not all, of this early work was broad-band, and whilst its value in establishing the overall structure of nebular envelopes should not be underestimated (cf Curtis 1918, Aller 1956), it is not in general a source of quantitative data useful for the construction of detailed geometric or ionisation structure models.

Broad-band photography is however unsurpassed in detecting faint extended nebulosity. This is best illustrated by Figure 1 which shows a beautiful exposure of NGC 7293 obtained by David Malin at the prime focus of the Anglo-Australian telescope. Faint hitherto undetected extensions, sweeping out to a radius of 18 arcmin, are revealed on this high contrast print.

In the last few years Goad and Chaisson (1973), Feibelman (1970) and others have published detailed monochromatic photographs or contour maps which show often quite dramatic changes in intensity distribution with ionisation potential. Figure 2 compares Hα and [NII]6584Å contour maps of NGC 6543 published by Phillips, Reay and

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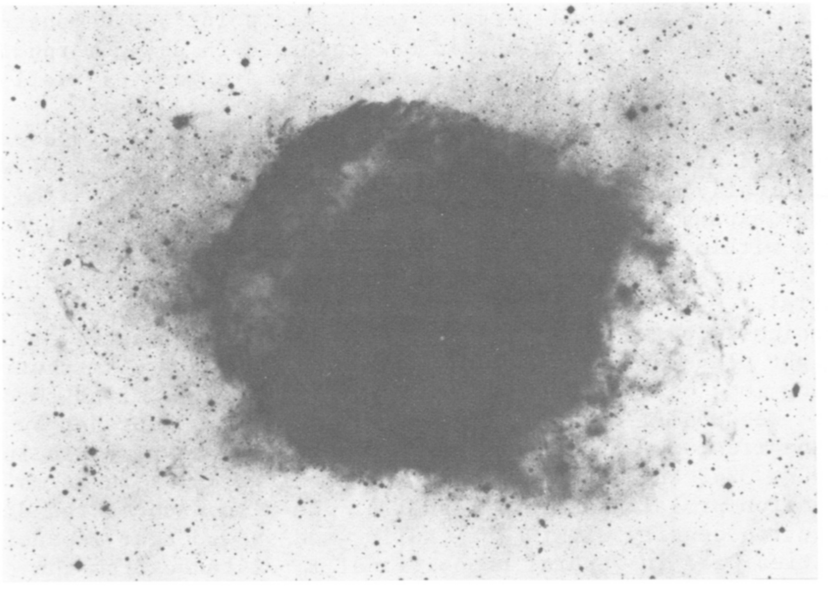

FIGURE 1. NGC 7293

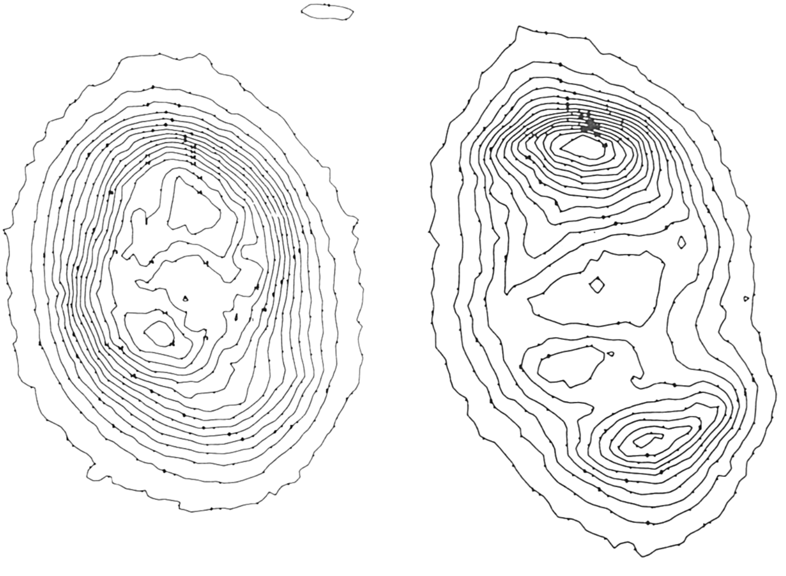

FIGURE 2. NGC 6543. (a) H_α 6563Å (b) [NII] 6584Å
North is at the top and east to the left.

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Worswick (1977) which illustrated well this point and demonstrates that considerable caution should be exercised in using morphological data for which the observational parameters are not very well known.

Internal velocities in planetary nebulae were first observed by Campbell and Moore (1918), but it was Wilson (1948, 1950) who systematically measured line splitting, interpreting his data in terms of envelope expansion, typically 20 km s^{-1}, and showed that stratification effects within the envelopes often led to ions of low ionisation potential expanding more rapidly than those with higher ionisation potential. Osterbrock et al (1966) interpreted the shapes of high dispersion emission line profiles, obtained at the centre of a number of bright planetary nebulae, in terms of a velocity distribution of emitting ions of typically 30 km s^{-1} in the line of sight through the shell. Weedman (1968) took the technique one step further by obtaining slit spectroscopy at points across 10 planetary nebulae, including NGC 7009, 3242 and IC418 and interpreted his results in terms of 3-dimension prolate spheroidal shells. He also deduced the distribution of electron density within the shells, and showed that expansion velocities were in general proportional to distance from the central star.

Theoretical work on the overall shapes of shells expanding from rotating stars supports to a large extent the general observational conclusion that planetary envelopes are spheroidal in shape, either prolate or oblate. Kirkpatrick (1976) has considered the development of shells under the influence of a continuous accelerative process (of the kind produced by ablation from the inner surface) and concluded that prolate forms would develop from an initially oblate spherical shell ejected by a rotating giant star. Louise (1973) discussed the development of gas shells ejected from a spherical rotating star. He showed that nebulae acquired prolate forms, although omitted to account for gravitational retardation during the ejection process. Phillips and Reay (1977) modelled the effect of gravitational braking, differential stellar rotation and radiation pressure on the development of ejected gas shells. They concluded that both oblate and prolate forms could develop, and that the principle forms observed in planetary nebulae can be explained reasonably well in terms of these factors alone.

To facilitate comparison with theoretical models my group at Imperial College have, over the last seven years used electronography to obtain monochromatic images of 50 or more planetary nebulae in a number of emission lines of widely differing ionisation potentials. The electronographic technique has the advantage over photography that it is linear over a wide density range, and does not suffer from reciprocity failure (Worswick 1975). It is suitable therefore for recording both the bright inner and faint outer regions of planetary nebulae on a single exposure. Figure 3 shows, for example the faint halo surrounding NGC 7027 recorded electronographically by Atherton et al (1979). The halo is about one thousand times fainter than the

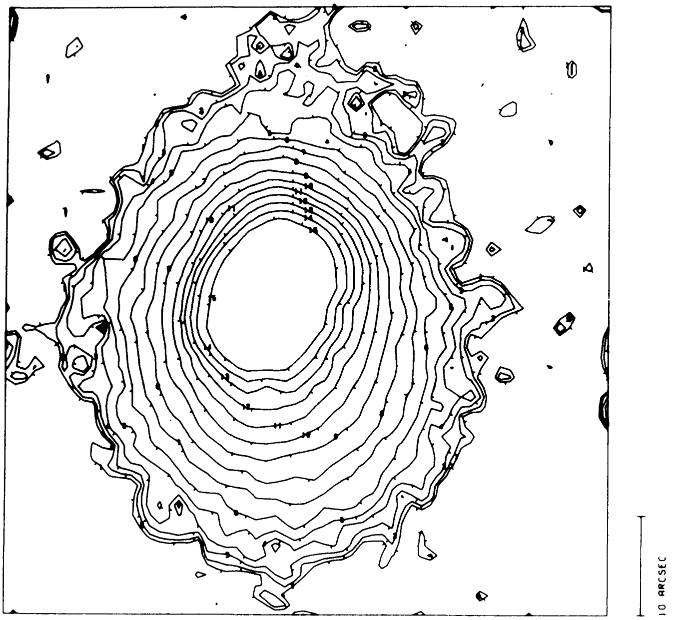

FIGURE 3. NGC 7027. Hα 6563Å map with contour levels set at logarithmic intervals.

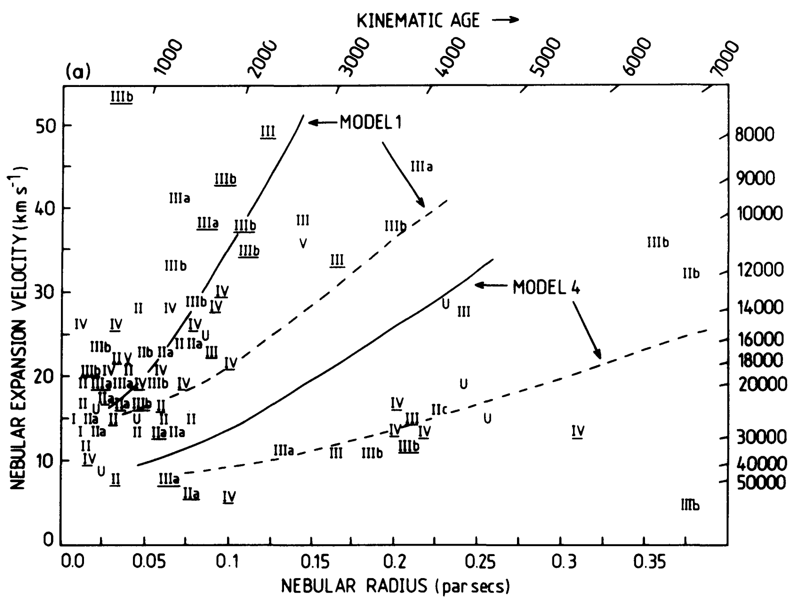

FIGURE 4. [OIII] expansion velocities versus radius for nebular envelopes. Points are shown as morphological classes (Verontsov-Velyaminov 1948). Full lines are model curves from Ferch and Salpeter (1975). Broken lines are same models but taking radius as being two times radius of maximum density.

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brightest part of the NGC 7027 image.

In general, because of its large dynamic range electronographic data is more capable than is photography of detecting underlying geometric symmetry which may otherwise be masked by large differences in surface brightness. Monochromatic electronography of NGC 5189 (Phillips and Reay 1982) and NGC 2440 (Phillips, Reay and Worswick 1980), for example, show these apparently irregular, chaotic objects to have a considerable degree of symmetry when viewed in sufficient detail. Both, in fact, show evidence for pairs of condensations symmetrically disposed about their respective central stars.

Reay and Worswick (1982) have used the linearity of electronography in order to ratio [OIII] 5007Å with 4363Å to map the electron temperature variation across 5 nebulae. Phillips, Reay & White (1982) have used the ratio technique to search for cool condensations in NGC 6302 and Atherton et al (1979) to locate the central star in NGC 7027 and estimate its brightness as $m_V = 19.4 \pm 1.0$.

Taylor (1977, 1979), and Hicks, Phillips and Reay (1976) have used Fabry-Perot interferometers to study velocity fields in planetary envelopes, and Atherton et al (1978) have combined monochromatic electronography with Fabry-Perot velocity field measurements to construct a 3-dimensional model for the HII region of NGC 6720 which shows it to have a closed spheroidal structure and not, as sometimes suggested necessary, a toroidal structure. Phillips, Reay and Worswick (1977) have shown using monochromatic electronography and re-analysing existing kinematic data, that the intrinsic form of NGC 6543 is spheroidal and not, as previously suggested, helical. The significance of this result is, more than anything else, in showing that an apparently complex nebula can be accommodated within a simple spheroidal model scheme.

EXPANSION OF THE HII REGION

Valuable insight into the evolution of planetary envelopes, and into the mechanism which drives or accelerates them, can be obtained by studying in a statistical way the relationship between expansion velocity and nebula radius.

In a comprehensive study of the dynamical effect of dust within nebular envelopes, Ferch and Salpeter (1975) have computed the accelerative effect of radiation pressure on the dust for a range of central star and nebular parameters. In general they predict an expanding envelope, with expansion velocity increasing with radius and a central 'hole' swept clear of gas by radiation pressure.

Bohuski and Smith (1974), Robinson, Reay and Atherton (1982) and Sabbadin and Hamzaoglu (1982) have made observational studies of the expansion velocity-radius relationship. Figure 4 (from Robinson et al, 1982) summarises their data and compares it with two of the

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Ferch and Salpeter models. The data points include data from Bohuski and Smith (1974), Johnson (1977), Wilson (1950) and others, but not the new data from Sabbadin and Hamzaoglu which appeared in print in June 1982. The agreement between theory and experiment is good, and Robinson et al conclude that there may be evidence in the data for two distinct velocity-radius sequences, consistent with Ferch and Salpeter (1975) Models 1 and 4. Sabbadin and Hamzaoglu confirm the general trend of increasing expansion velocity with radius up to 0.2 parsec beyond which they see a fall in expansion velocity which they attribute to possible interaction of the envelope with the interstellar medium.

Thus we appear to have some quantitative agreement between theory and observation which may well be improved upon by deriving the envelope expansion velocity from a 3-dimensional model of the nebula rather than from a single point measurement. The importance of the agreement lies in the ability it gives to attribute a relative age to a nebula and so to study evolution of the 3-dimensional forms.

NEW METHODS

Returning to the methods by which kinematic and monochromatic isophotometric data is acquired, it is worth noting the limitations in current technique and asking what modern instruments and electronic detectors enable us to achieve.

Photographic photometry is limited by dynamic range and calibration difficulties (although not everyone would agree with that!)

Electronography overcomes these difficulties, but has its own limitations to do with difficulties in flat fielding caused by poor quality electronographic emulsion. This conspires to limit the achievable photometric accuracy obtainable with an electronographic device to approximately 2%.

Kinematic studies are limited to simultaneously measuring a number of points along a spectrograph slit at a spatial resolution determined by the slit width, or to measuring points sequentially with more luminous Fabry-Perot interferometers. Spatial resolutions in this latter case are usually 5 arcsec or worse.

Multislit spectrometers and Fabry-Perot interferometers working in non-classical mode (see for example Meaburn, 1976) have been used to achieve better spectral and spatial coverage, but none are completely satisfactory.

The advent of imaging electronic detectors has however shown the way to an instrument which my colleague and I at Imperial College and at the Anglo-Australian Observatory now use to obtain simultaneous seeing limited photometry and kinematic information across the envelopes

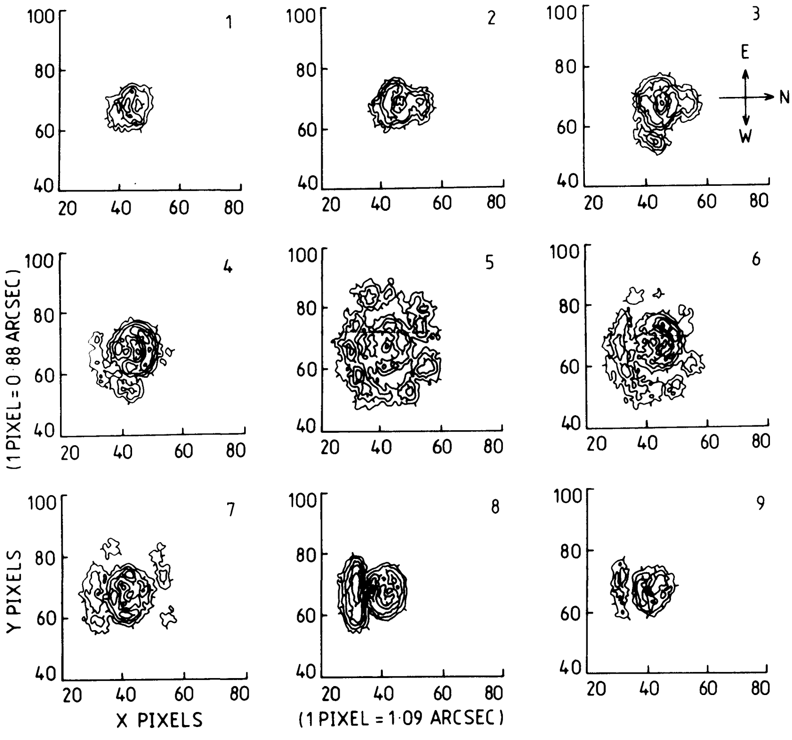

FIGURE 5. NGC 2392. A sequence of monochromatic slices through the [NII] 6584Å line. Resolution 0.33Å, spacing 0.66Å. Wavelength increases with frame number.

of planetary nebulae. The instrument is described fully by Atherton et al (1982), suffice to say it is a large aperture servo-controlled scanning Fabry-Perot interferometer which uses as a detector the Image Photon Counting System (Boksenberg 1972). A range of etalons is available to give spectral coverage in the green and red with a resolving power of up to 50,000. The instrument is scanned under microprocessor control and simultaneously records an array of up to 500 by 500 spectra over a field of up to 9 arcminute in diameter.

The data can be presented either as an array of spectra or a series of monochromatic slices. A comprehensive data reduction package is available on the SERC STARLINK image processing system to extract from the data emission line velocities and intensities, monochromatic maps, simulated slit spectra and a host of other parameters.

The beauty of this technique is that we acquire kinematic and photometric data simultaneously. The data is recorded at 'seeing limited' spatial resolution and is stored digitally, so making it

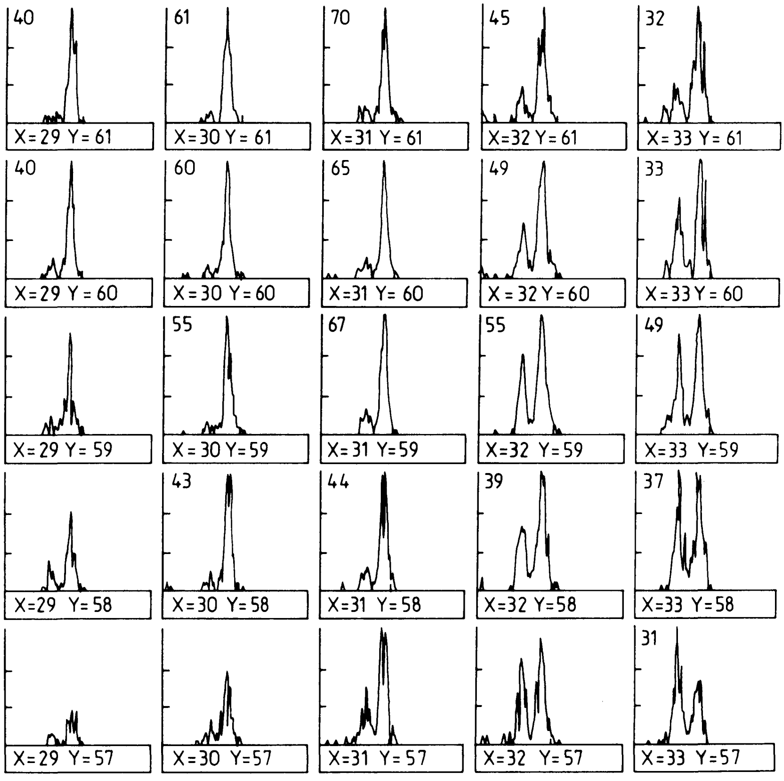

FIGURE 6. NGC 2392. Sample spectra from the [NII] array. Wavelength scans from red to blue. When maximum count exceeds 30, its value is indicated in top left corner

easier to extract, for example, electron density and temperature maps from forbidden line ratios and to attempt on-line 3-dimensional model fitting.

Figure 5 shows an example of [NII] 6584Å data obtained on NGC 2392, Figure 6 gives a 5 x 5 sample from the grid of 128 x 128 spectra we have obtained across the envelope, and in Figure 7 we show an image of NGC 5189 with synthetic spectra reconstructed from our data array. The inner regions of NGC 5189 can be interpreted on the basis of this data as a ring of condensations expanding from the central star at 23 km s^{-1} and lying in a plane, the normal to which is tilted an an angle of 80° to the line of sight.

CONCLUDING REMARKS

A full size TAURUS data 'cube' consists of 500 x 500 pixels with 100 or more interferometer steps and 8 bit numbers - that is

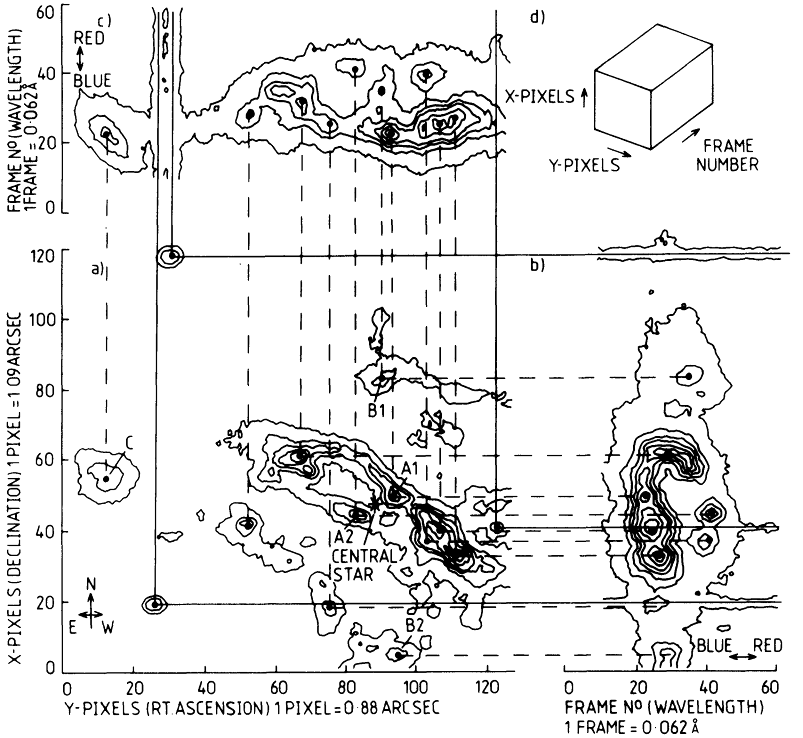

FIGURE 7. NGC 5189. (a) [NII] 6584Å contour map. (b) Synthetic spectral line obtained by adding X PIXEL-WAVELENGTH slices from the data array (c) Synthetic spectral line obtained by adding Y PIXEL-WAVELENGTH slices. (d) Schematic data cube.

a staggering 200 Mbits of data.

In practice we use smaller data arrays, perhaps 150 x 150 pixels, but even so produce 18 Mbit data sets for a typical one hour observation of say the [SII] 6717Å line in NGC 2440.

The CFH Telescope and the new UK observatory in the Canary Islands will be equipped with similar wide field instruments. In the next ten years I anticipate that imaging Fabry-Perot or Michelson interferometers will be standard equipment at all major observatories, and with infrared array detectors they will be capable of working at wavelengths to 10 μm and beyond.

The problem will then not be one of how to acquire sufficient data, but how to cope with the data we have acquired.

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KAHN: Could you give us an indication of the likely age of the PN (with ansae) that you have just been talking about?

REAY: The outer envelope of A 30 has an expansion velocity of 40 km s^{-1} and a kinematic age of 10^4y. The system of inner ansae has a radial velocity $\simeq$ 25 km s^{-1} and an actual expansion velocity of 35 km s^{-1} if we assume a projection angle of 45°. The kinematic age of the ansae is, therefore, about 1.5 x 10^3y. A distance of 1.4 kpc has been assumed.

SURDEJ: How many PN are known to show double structure in their envelopes? What are the radial velocities of these structures? Has any mechanism been proposed to explain the formation of such structures?

REAY: From my own observations, I have found strong evidence for pairs of ansae in NGC 2440, NGC 5189 and NGC 6826. In the first two objects, there is some evidence for multiple pairs at different position angles. A30 has two pairs of ansae and recent evidence suggests that NGC 7026 also has ansae. The prototype object is, of course, NGC 7009.

Radial velocities of ansae are typically 20 km s^{-1}, similar to the expansion velocities of nebulae. I know of no mechanism proposed for the ejection of multiple pairs of ansae. Could it be symmetric ejection from a precessing central star? I would be interested in hearing from anyone with ideas on this topic.

ALLER: It is extremely important to have monochromatic isophotes for PN. The discordances between different sets of line intensity measurements arise often not from errors in the data but from differences in what was actually observed. Photoelectric measurements often give the integrated light from the entire nebula, whilst IDS or IPCS observations are necessarily restricted to small strips or areas. With isophotic contours, we can at least correct some lines for this effect. Such observations are especially important to relate IUE and optical observations.

KALER: Are the Greig and Khromov and Kohoutek classification schemes still valid in the light of the new work?

REAY: We have not yet observed a sufficiently large number of nebulae to enable me to answer your question. My initial impression is that the current classification schemes are valid but inadequate.

MALLIK: Which distances did you use in the plot of V against R?

REAY: All distances are from Acker (1978, Astron. Astrophys. Suppl. 33, 367).

OSTERBROCK: The monochromatic images are a very important step forward in your work. In the case of NGC 6543, can you explain how the two "closed shell" models for Hα and [N II] combine to give the helix appearance as their sum? Are the two models tipped? Do other helix nebulae - for instance NGC 7293 - have similar morphology?

REAY: Electronographic observations of NGC 6543 were made through narrow band (≈ 10 Å) filters centred on [O I], [S II], [N II], [O III], [O II], Hβ and other lines. The low ionisation structures are similar but quite different from [O III] and Hβ. None of the lines show strong evidence for a helical structure. My suggestion was that the helical structure may be an illusion produced by adding high and low excitation images. Even if real, the structure can be accommodated in a simple, three-dimensional, kinematic model. However, new 20 cm VLA data to be presented at this conference by Bignell suggest that the helical structure may, indeed, be real.

NGC 7293 is too large for me to observe, but like NGC 6720 the overall structure can be accommodated within a three-dimensional closed shell model.

KEYES: Have you used your observations of other emission lines to obtain three-dimensional maps of electron density (from [S II] or [O II]) or electron temperature ([O III]) in any objects? If so, what are the ranges of N_e and T_e?

REAY: I have obtained data in the [S II] λλ 6717, 6731 lines for NGC 2440, NGC 5189 and a number of other PN which I shall use to construct three-dimensional electron density maps. The data have not yet been reduced.

My colleagues and I have published electron temperature maps of a number of PN using two-dimensional electronographic data ([O III] λ 5007 and λ 4363). We find temperature changes of typically a few hundred degrees over the [O III] - emitting region (1982, Mon. Not. Roy. Astron. Soc. 199, 581).

CARSENTY: Leaving the small-scale structure aside and considering the general structure, do you find any cases of special symmetry (cylindrical, prolate or oblate spheroids)?

REAY: It is difficult to leave aside the condensations and look at the underlying structure. In the cases of NGC 2440 and NGC 5189, the condensations appear to dominate the structure to such an extent that their removal leaves very little behind! The inner condensations in NGC 5189 do, however, lie in a ring centred on the central star, in a plane the normal to which is tilted at 80^o to the line of sight, and are expanding at about 25 km s^{-1} from the star. In a sense, this is the underlying structure; it is very similar to that of NGC 650-1.

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