Astron. Astrophys. 240, 137–141 (1990)

ASTRONOMY AND ASTROPHYSICS

Kinematic studies of five galactic planetary nebulae

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Received April 24, accepted May 17, 1990

Abstract. High resolution Fabry-Perot observations have been made to determine the velocity structure of five planetary nebulae and to subsequently relate the observations to the morphology of the objects. We present here new kinematic data on one of these planetary nebulae (NGC 5882) and supplement existing observations in other cases. We also investigate the effect of aperture size on expansion velocity in NGC 5882 and compare observed results with values predicted from models. We report on and try to quantitatively account for the unusual triple-peaked line profile observed in the bipolar nebula NGC 2818.

Key words: spectroscopy: Fabry-Perot – lines: profile – planetary nebulae: expansion velocity

1. Introduction

High-resolution spectroscopic observations of planetary nebulae (PNe) yield information on their kinematics. Such kinematical information can be modelled to understand the morphology of the object. Even though there exists a certain amount of uncertainty, as to the morphology that needs to be assumed to explain the observations, gross features of the structure of the nebula can still be determined. In this work we study the kinematics of four southern PNe viz., NGC 2818, 5882, 6302, IC 4406 and of the northern PN NGC 650/1 using Fabry-Perot (F.P.) spectroscopy and relate the observations with the morphological aspects.

2. Observations

Observations were made at the Cassegrain focus of the 1-m-reflector at the Vainu Bappu Observatory, Kavalur, between Dec. 1986 to March 1988. The instruments used were: (i) A high-resolution piezo-scanning F.P. spectrometer which employs two separate etalons for coverage of the blue and red spectral regions. The spectrometer has a velocity resolution of 10 km s^{-1} (corresponding to twice the expansion velocity) in both the [O III] and Hα lines. Instrument performance and stability were tested in between observations by using the 6598 Å line from a neon spectral lamp. The details of the spectrometer are given elsewhere (Banerjee et al. 1987). (ii) A pressure scanned F.P. spectrometer for [O III] line studies in NGC 650/1 and NGC 2818. Performance and wavelength calibration of the instrument (required specially while mapping NGC 650/1) were done using the 5015 Å line from a helium lamp.

The detector was a dry-ice-cooled, S-20 photomultiplier tube with an average dark count rate of 5–10 counts s^{-1}. An integration time of 1 s/step for data collection was used in all the scans. The details of the observations are given in Table 1 and indicate the emission lines studied, the apertures used, number of profiles obtained, the SNR for a single scan at the peak of the profile (SNR defined as per Dopita 1972) and the emission line parameters observed in the different PNe. The scans, in general, have been coadded to improve the SNR and the resulting profiles analysed. The typical error in determining the position of a peak and, hence, in the expansion velocity is ~1 km s^{-1} for both the piezo-scanned and pressure-scanned F.P.S.

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3. Results and discussion

3.1. NGC 5882

This object appears as a spherical blob with a radius of 7″.5 (Perek & Kohoutek 1967). High resolution slit spectra of this PN have been obtained by Ortolani & Sabbadin (1985). Their results give expansion velocities of 16.5 km s^{-1} and 23.5 km s^{-1} in the [N II] and Hα lines respectively and also indicate that the intensity of the emission from the blue component is less than that from the red. Measurements of [O III] which could throw light on the motions in the inner regions of the nebula are not available for this object. In Fig. 1 we show the [O III] and Hβ line profiles in the central region of NGC 5882 – each profile has been fitted by two gaussians. The profiles indicate an expanding shell with $V_{exp}=12.5$ km s^{-1}, the relative intensities of the receding and approaching velocity components being consistent with the findings of Ortolani & Sabbadin (1985). In Table 1 we give the parameters of the Gaussian fits to the profiles. A few points may be noted from the above table and also from the shape of the profiles. (i) The expansion velocity in the nebula does not decrease when the aperture is increased from 8″ to 15″. In fact, it remains constant and shows a tendency to increase marginally but close to the errors of observation which may not be realistic. One can however state definitely that there are no indications for a decrease. (ii) The widths of the individual components show a marginal increase (again close to the limits of the errors) as one goes from 8″ to 15″ aperture sizes. (iii) Comparison of the profiles obtained with aperture sizes of 15″ and 30″ show, close similarity in shape, line widths and expansion velocities. Further no change in the level of signal was obtained between these two apertures (15″ and 30″). From this it may be concluded that the bulk of the

Table 1. Observational details and emission line parameters for the observed PNe

Object	Emission line	Aperture used (″)	Position on nebula	Number of profiles	SNR[a]	Widths and relative intensity of profile components from gaussian curve fitting						V_{exp}[b] (km s^{-1})
						FWHM$_1$	FWHM$_2$	FWHM$_3$	I$_1$	I$_2$	I$_3$	
NGC 5882	[O III]	8	Centre	4	5	24.0	22.5		0.88	0.86		11.0
	[O III]	15	Centre	4	15	26.5	25.0		0.83	0.89		12.0
	[O III]	30	Centre	4	15	27.0	27.5		0.72	0.90		12.0
	Hβ	30	Centre	4	8	31.2	35.0		0.50	0.89		13.0
NGC 2818	[N II]	45	Centre	2	8	24.0	19.7	21.0	0.62	0.95	0.90	27.0
	[O III]	60	Centre	1	5	9.5	22.0	20.0	0.47	1.0	0.91	23.0
	Hα	45	Centre	4	5	32.5	16.3	27.5	0.95	0.75	0.50	25.0
NGC 650/1	[O III]	30	Centre	6	8	28.0	29.0		0.46	0.70		8.0
	[O III]	30	SW[c]	3	10	8.0	32.0		0.25	0.96		12.0
	[O III]	30	NE[c]	2	10	34.0	10.6		0.98	0.30		15.0
NGC 6302	[N II]	30	Centre	6	25	24.0	31.0		0.55	0.94		12.5
IC 4406	[O III]	45	Centre	6	10	14.0	18.0		0.53	0.73		5.0

[a] SNR (signal-to-noise ratio) values for a single scan indicated at the peak of the profile
[b] The errors in determining V_{exp} and FWHM values are ~1 km s^{-1}
[c] See text on NGC 650/1

emission is from a 15″ area which coincides with the spatial extension of NGC 5882.

However, for a spherically symmetric nebula (as in the case of NGC 5882) it is expected that the expansion velocity should decrease when the aperture size is increased. The expected decrease in line splitting has been quantitatively worked out by Robinson et al. (1982) but only for values of the projected aperture size less than 0.5 times the nebular radius. In general the line profile expected from the nebula can be obtained in the following manner: along a line of sight (l.o.s.), the intensity $I(v)$ at a particular velocity v, emitted by ions with different bulk velocities at different distances [i.e. $v=v(r)$] and further broadened in velocity by thermal motion and turbulence, can be represented by the integral (cf. Osterbrock et al. 1966; Osterbrock 1974)

$$I(v)=\text{Const.}\int_{-\infty}^{+\infty} n_e^2(r)\, e^{-\frac{[v(r)-v]^2}{[2kT/M+V_T^2]}}\,\mathrm{d}r. \quad (1)$$

Here k is the Boltzman constant and n_e is the electron density. The turbulence is assumed to be Gaussian and is characterised by the most probable turbulent velocity V_T. It is also assumed that the nebula is isothermal with a temperature T and that there is no attenuation of the emission due to dust.

The effect on $I(v)$ due to a finite aperture is obtained by evaluating the integral of Eq. 1 for all l.o.s. included in the aperture and therefore Eq. 1 becomes a triple integral in r, θ, ϕ (if spherical coordinates are chosen). The limits of integration for r, θ, ϕ are decided by the size of the aperture subtended at the nebula and by the geometrical form chosen for the nebula. The final instrument-broadened emission profile is obtained by convolving $I(v)$ with the instrument function $F(v)$, i.e.,

$$I_{\text{final}}(v)=\int_{-\infty}^{+\infty} F(v'-v)I(v')\mathrm{d}v'.$$

We have evaluated the emission profile by the above procedure for a spherical shell and for an oblate spheroidal shell. The reason for the choice of the second geometrical form is two fold viz., (i) such a form will appear spherical (like NGC 5882) when projected in the sky with the minor axis along l.o.s. and (ii) if it is assumed that $v\propto r$ in the nebula (as is usually done in PNe), then increasing aperture sizes should take in elements of the shell at larger values of r (the radial distance from the central star) and therefore having higher velocities. However these higher velocity components, when projected along the l.o.s., will be diminished by corresponding greater amounts since the projection angle increases for these components. Since it is difficult to conclude a priori as to which of the above two factors will be dominant, it is worthwhile to verify whether an oblate spheroidal form can yield constant or increasing expansion velocities with increasing aperture size.

In constructing the line profiles we have assumed that $n_e\propto r^{-n}$. Further, shell thickness is assumed to be small compared to the dimensions of the nebula. This is consistent with the filling factor $\varepsilon=0.2$ calculated for this nebula from the relation (Pottasch 1984)

$$n_e\varepsilon^{1/2}=2.74\,10^4\left[\frac{F(H\beta)T^{0.88}}{\theta^3 d}\right]^{1/2}$$

where $F(H\beta)$ is the $H\beta$ flux, T is the temperature, d is the distance to the nebula and θ is the angular radius of the shell. Values of T were adopted from Kaler (1986), n_e, θ and $F(H\beta)$ from Pottasch (1984) and d from Weinberger (1989). It may be pointed out that the uncertainty in the distance is $\leq 50\%$.

Numerical integrations involved in evaluating the line profiles were done using a gaussian quadrature routine (Press et al. 1986). Different values of the index $n=0, 1, 2,$ and 3 in the relation $n_e\propto r^{-n}$ were tried. We find that, for both spherical or oblate spheroidal shells, the expansion velocity decreases with increasing aperture size. This is true even when extreme values of eccentricity are chosen for the geometry of the oblate spheroidal shell. Further in the above model, the total width at half-intensity

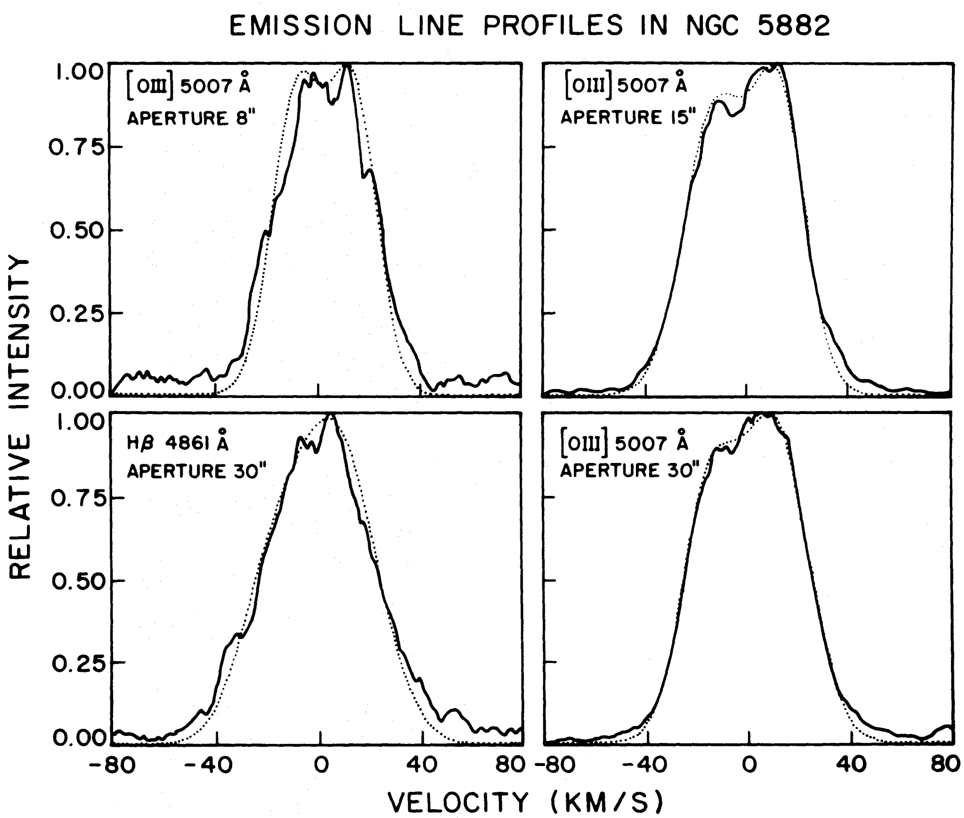

Fig. 1. The [O III] 5007 Å and Hβ 4861 Å emission line profiles in the central region of the planetary nebula NGC 5882. The different aperture sizes used for the observations are indicated. The dotted lines represent a double-gaussian fit to the observed data which is shown by the continuous line

of the profile is found to decrease with increasing aperture size. For the sake of comparison, we note for a sperical shell that the decrease in the line splitting due to an aperture subtending 25% of the nebular diameter is about 3% in the Robinson et al. model (1982) and about 4% in our study. From the above work it is seen that the observed kinematic field in NGC 5882 is in variance with what is expected of a spherically symmetric nebula. It may therefore be conjectured that there is more structure to NGC 5882 than its apparent spherical shape shows. High spatial resolution images of the object are needed to confirm its morphology. In this context it may be noted that Weller & Heathcoṭe (1987) have detected a faint extended halo around the object extending to 60″.

3.2. NGC 2818

This object is unique among galactic PNe in the sense that it is the only known object which is probably associated with an open star cluster. The overall structure of this PN comprises of an hour-glass form (of angular dimensions 60″ × 130″) oriented in the NS direction with the narrow waist oriented in the EW direction (Dufour 1984). The echelle spectra of NGC 2818 obtained by Dufour (1984), with a slit of width 1$''.4$ in position angle 0°, yield (V_{exp}) [N II] = 51 km s^{-1} and (V_{exp}) [O III] = 53 km s^{-1}. Since Dufour mentions that the echelle spectra show a complex velocity structure it is not clear whether the expansion velocities quoted by him are only for the central region or averaged over the length of the slit. Our observations in the central region give V_{exp} values of 27 and 23 km s^{-1} in the [N II] and [O III] lines respectively, which are significantly smaller than those reported by Dufour and which may, to a certain extent, be the consequence of the large aperture used by us (ref. Table 1). Our values, however, agree a little better with (V_{exp}) [O III] = 40 km s^{-1} measured by Meatheringham et al. (as quoted in Weinberger 1989).

What is more interesting is, however, the structure of the line profiles obtained by us (Fig. 2). As may be seen from Fig. 2, an unusual triple structured profile is obtained in each of the emission lines. Such a triple component profile has probably been observed only in NGC 650/1 (Taylor 1979) and IC 4593 (Anandarao & Banerjee 1988). The expansion velocities quoted by us in the previous paragraph are between the outer two components of the profiles. We advance a possible explanation for the shape of the profiles. Well mapped bipolar PNe indicate that the expansion velocities in the waist of such PNe are smaller than those in the hour-glass lobes (Icke et al. 1989 for NGC 2440; Sabbadin 1981 for NGC 650/1 and Meaburn & Walsh 1980b for NGC 6302). Mechanisms for PNe formation which explain how such velocity fields may arise have been suggested by Kahn & West (1985) and Icke (1988). With reference to NGC 2818, since the aperture sizes used cover both the waist of the nebula and significant parts of the hour-glass lobes, it appears that the two outer components of the observed profiles correspond to the faster expanding lobes and the central component to a slower expanding toroidal waist.

3.3. NGC 650/1

NGC 650/1 is a high-excitation PN which appears as a bright dog-bone shaped bar oriented at PA 40° in short exposure images (Minkowski 1964). Longer exposures of the object show the

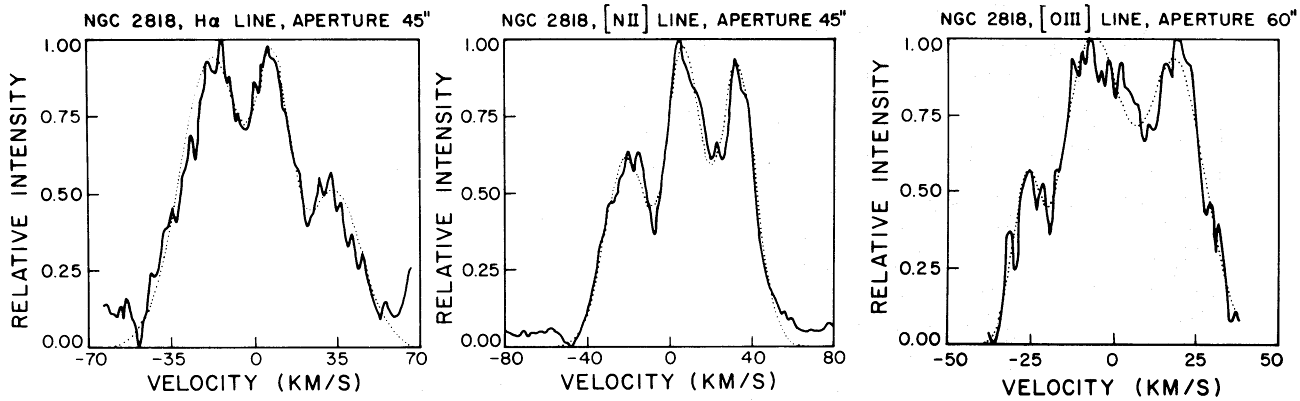

Fig. 2. The Hα6563 Å, [N II] 6584 Å and [O III] 5007 Å emission line profiles, respectively, in the central region of the planetary nebula NGC 2818. The dotted lines represent a three component gaussian fit to the observed data which is indicated by the continuous line

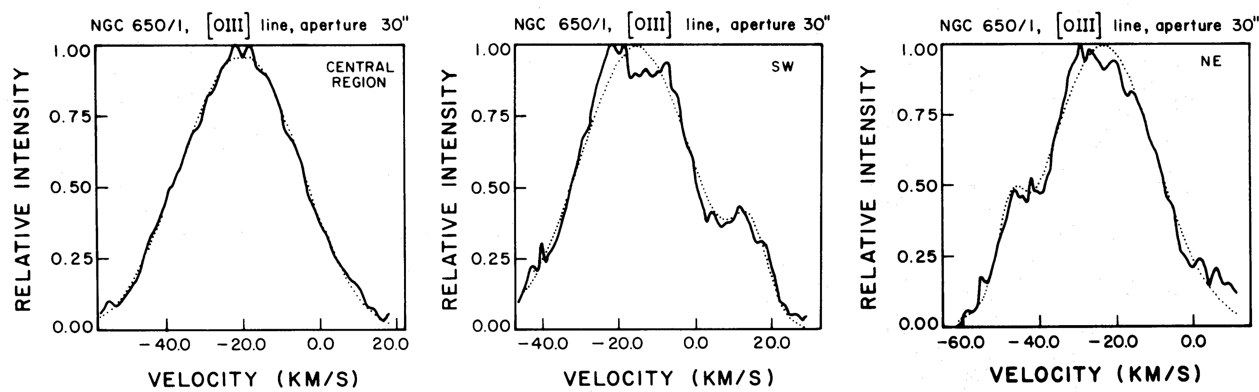

Fig. 3. The [O III] 5007 Å emission line profiles at three different positions in the planetary nebula NGC 650/1. Apart from the central region, the other two positions indicated by NE and SW are situated along position angles 45° and 225° respectively and at a distance of 20″ away from the central star. The dotted lines represent a double-gaussian fit to the observed data which is shown by the continuous line. A systemic velocity of -20 km s^{-1} for the central region has been adopted as per the work of RCP and SH81 (see text)

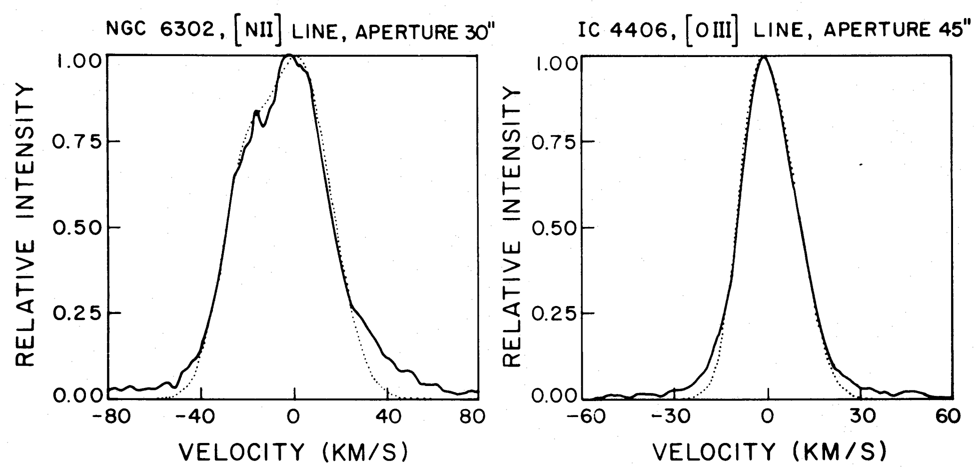

Fig. 4. The [N II] 6584 Å and [O III] 5007 Å emission line profiles in the planetary nebulae NGC 6302 and IC 4406 respectively. The dotted lines represent a double-gaussian fit to the observed data which is indicated by the continuous line

presence of a fainter hour-glass structure projected almost perpendicular to the central bar. Considerable filamentary structure and condensations are seen in the lobes. The [N II] velocity structure of this PN has been studied by Recillas-Cruz & Pismis (1984), Taylor (1979) and Sabbadin & Hamzaoglu (1981) (hereafter RCP, T and SH81 respectively). The only existing study in [O III] is from the echelle slit spectrographs of Sabbadin & Hamzaoglu (1982 – hereafter SH82). Our [O III] observations are restricted to three positions on the object, viz., the central region and two other positions symmetrically opposite in the NE and SW directions and 20″ away from the central star along the bright central bar. An aperture of 30″ was used in each position. Our observations are in a sense analogous to Taylor's since his observations are also in 2 positions (in the NE and SW ends of the central bar) except that the aperture used by him is 40″ and the positions studied are 25″ away from the central star though in the same direction.

We reproduce in Fig. 3 the line profiles obtained in NGC 650/1 in the 3 different positions – each of the curves has been fitted by two gaussians. We find from the profiles of Fig. 3 that the NE position of the central bar is slightly blue shifted by 5 ± 2 km s^{-1} and the SW position is redshifted by 6 ± 2 km s^{-1} with respect to the velocity of the central region. Such a tilt to the [O III] velocities is also found in the [N II] observations of T, RCP, and SH81. This has been interpreted by SH81 to imply that the central bar is actually an elliptical ring in projection. We note that the profiles of Fig. 3 are not too well fitted by two gaussians implying that there may be more velocity components in the line of sight. This fact is supported by T's observations which show a triple-structured profile in both the NE and SW ends of the central bar and also the rather complex velocity structure found in this object by RCP and SH81. It is also seen that the profile in the central region does not show any line splitting inspite of several scans being taken in this position. Further, the V_{exp} value (deduced from the double-gaussian fit) in the central region is found to be 8 km s^{-1} which is much smaller than the value $V_{exp} = 38$ km s^{-1} quoted by SH82. Even a mean $V_{exp} = 12$ km s^{-1}obtained by averaging expansion velocities over the three positions of our observations still falls short of SH82's value. However, we tend to have confidence in our results since instrument performance was checked several times during the observations and V_{exp} measurements of other objects during the same night give consistent results.

3.4. NGC 6302 and IC 4406

In these two objects V_{exp} measurements have been made only in the central region. We show in Fig. 4 the line profiles obtained in these two PNe. The [N II] profile in NGC 6302 is not clearly resolved into two components associated with an expanding shell but shows a tendency of line splitting in all the scans. The expansion velocity is found to be 12.0 km s^{-1} which is consistent with an average $V_{exp} = 8$ km s^{-1} measured by Acker (1976) in different ions. However, it must be pointed out that a complex velocity field exists in this nebula (Meaburn & Walsh 1980b) and that the expansion velocity varies significantly over the nebula. We also do not find any evidence for wing-broadening in the [N II] profile (obtained with a high SNR) similar to the broad and unique 800 km s^{-1} wings found in the [Ne V] profiles by Meaburn & Walsh (1980a) and associated probably with emission from an ionized stellar wind. There appears, however, a conspicuous asymmetry in the redward wing of the [N II] profile which does not fit the model double gaussian profile (dotted line) indicating probably an additional structure in the velocity field.

The [O III] profile in IC 4406 shows a clean gaussian like profile with no hint of line-splitting. The narrow FWHM of the profile (20 km s^{-1}) suggests a small expansion velocity. A double gaussian fit indicates $V_{exp} = 5$ km s^{-1}. Alternatively one can use the method of Robinson et al. (1982) who have shown that when line splitting is absent, the expansion velocity can be estimated from the relation $2V_{exp} \sim W(\text{intrinsic})$, where W(intrinsic) is the intrinsic FWHM of the profile and is related to the observed FWHM of the profile by

$$W^2(\text{observed}) = W^2(\text{intrinsic}) + W^2(\text{thermal}) + W^2(\text{instrumental}).$$

The above approach yields $V_{exp} \sim 6$ km s^{-1}, a value which agrees well with that derived from a double gaussian fit and also with V_{exp} values measured by other observers (Acker 1976; Robinson et al. 1982).

4. Conclusions

The main conclusions of this work are:

(i) From an expansion velocity versus aperture study it appears that NGC 5882 has a more complex morphology than is apparent from its low-spatial resolution image.

(ii) An unusual triple-component profile is obtained in NGC 2818 which is accounted for by the velocity field structure that is expected in bipolar PNe.

Acknowledgements. BGA and DPK acknowledge the excellent technical support extended to us by N.S. Jog, K.S.B. Manian, R.K. Mahadkar, and F.M. Pathan of the Infrared Astronomy group (P.R.L.) and also by the telescope staff of the Vainu Bappu Observatory during observations. This work was supported by the Department of Science and Technology and the Department of Space, Government of India.

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