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# Morphology of the bipolar planetary nebula NGC 2346 from emission line profile studies

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**Summary.** High resolution observations of H$\alpha$ 6563 Å, [O III] 5007 Å and [N II] 6583 Å emission lines in the bipolar planetary nebula NGC 2346 are presented. Expansion velocities ($V_{exp}$) of $8\pm1$ km s$^{-1}$ in the [O III] line and $11\pm1$ km s$^{-1}$ in the [N II] line are observed in the central region. An expansion velocity of $7.5\pm1.0$ km s$^{-1}$ in the [O III] line is observed in a position 10 arcsec away from the centre, in the NE lobe of the nebula. From the widths of the H$\alpha$ and [N II] lines, an ion temperature of $T=10\,650\pm2950$ K and a turbulent velocity $V_T=16\pm2$ km s$^{-1}$ are derived. Using the detailed radial velocity mapping done by Walsh, a morphological model for the nebula is presented. We suggest that the observed relative intensities of the approaching and receding components of emission lines in this nebula may very well be interpreted as due to the particular line-of-sight geometry in which the nebula is oriented.

## 1 Introduction

The planetary nebula NGC 2346 (PK 215+3°1) is a complex object yet to be fully understood. Morphologically it has a bipolar hour-glass structure (Cohen & Barlow 1975) oriented approximately in the N–S direction with a narrow waist oriented along the E–W. The detectable central star has been found to be of type A0 III by Kohoutek & Senkbeil (1973) and of type A5 V by Mendez (1978). To account for the high excitation spectrum of NGC 2346 it was first suggested by Kohoutek & Senkbeil (1973) that the A type central star has a hot subdwarf companion. Observations of the central star have confirmed that it is a single lined spectroscopic binary with a period of 16 days (Mendez & Niemala 1981). Since 1981, photometric observations of the central star have revealed periodic variations in the light curve (Mendez, Gathier & Niemala 1982; Kohoutek 1983; Roth, Echevarria & Tapia 1984; Schaeffer 1985) and subsequent observations (Acker & Jacniewicz 1985; Jacniewicz & Acker 1986) have further shown a dephasing of the light curve.

Walsh (1983) has observed the nebula using a slit spectrograph orienting the slit along the N–S direction and has obtained [N II] and H$\alpha$ line profiles along three parallel directions separated by

15 arcsec from each other. Radial velocity measurements in the [N II] line show secondary structures and wings in the line profiles. In this paper we report high-resolution observations of NGC 2346 in the Hα, [N II] and [O III] lines. We present a discussion of the interpretation of the widths of these line profiles. Furthermore a possible morphology of the nebula in the line-of-sight, based on the observations made by Walsh (1983), is discussed.

## 2 Observations and results

Using a high-resolution Fabry–Perot Spectrometer (FPS) at the Cassegrain focus of the 1-m reflector at Kavalur Vainu Bappu Observatory, we have obtained profiles of the emission lines Hα 6563 Å, [N II] 6583 Å and [O III] 5007 Å in the nebula NGC 2346. Two FPS systems were used:

(i) a high-resolution piezo-scanned servo-controlled FPS (Banerjee *et al.* 1987) for line studies in the spectral region 6000–7000 Å with a velocity resolution of $\sim 10\,\mathrm{km\,s^{-1}}$;

(ii) a pressure-scanned optically-contacted FPS (an improved version of the one described by Sahu, Desai & Jog 1984) for line studies in the spectral range 4500–5500 Å with a velocity resolution of $\sim 5\,\mathrm{km\,s^{-1}}$.

These observations were made on three occasions – 1986 February, 1986 December and 1987 February–March. For the Hα 6563 Å and [N II] 6583 Å lines, a field aperture of 15 arcsec centred

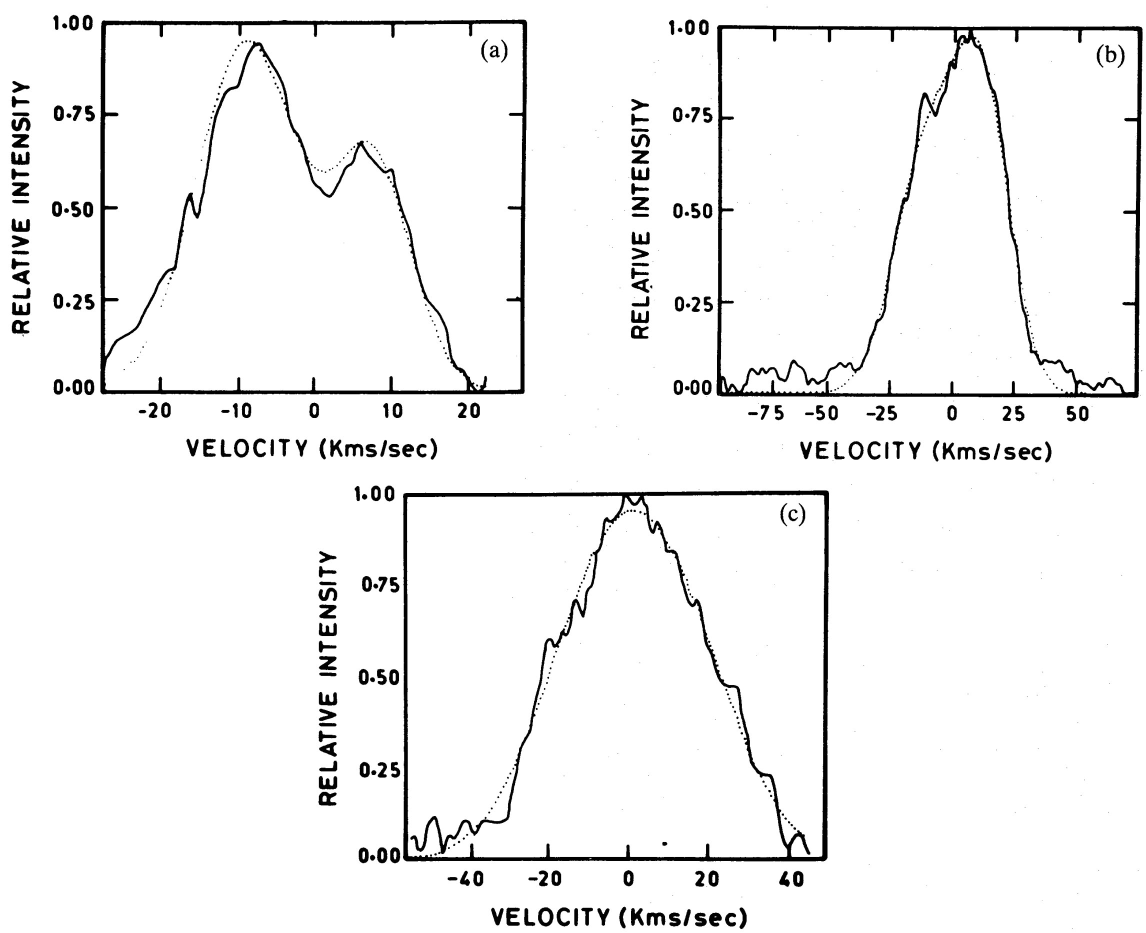


**Figure 1.** (a–c) The [O III] 5007 Å, [N II] 6583 Å and Hα 6583 Å line profiles (indicated by the continuous lines) from the central region of NGC 2346 are shown in the three figures respectively. Each profile has been fitted by two Gaussians indicated by the dotted line.

on the object was used. In the [O III] line the object was studied in three different positions. In each position an aperture of 8 arcsec was used. The positions observed are as follows:

(i) the central region of the nebula, designated as position 1;
(ii) position 2 placed 10 arcsec away from the centre and in the NE lobe of the nebula at an angle inclined by 75° to the RA axis;
(iii) position 3 placed diametrically opposite to position 2 at a distance of 10 arcsec from the centre and in the SW lobe.

In the central region, eight scans in [O III], four in [N II] and three scans in H$\alpha$ were obtained. An integration time of 1 s was used for all the scans. Co-adding of the scans was done to improve the signal-to-noise ratio which ranged typically between 5 and 7 at the peak of the profiles. In position 2 in the [O III] line two scans were obtained and these were co-added. In position 3, although two scans were taken, the data obtained were not reliable due to fluctuating sky conditions. The resultant profiles in the central region are shown in Fig 1(a)–(c) for the [O III], [N II] and H$\alpha$ lines respectively. The [O III] line profile in position 2 is shown in Fig. 2. The [O III] profile in the central region shows a well defined separation between the blue and red components associated with an expanding shell (Fig. 1a). In the case of the [N II] profiles Fig. 1b), although a well resolved split is not clearly indicated, a pronounced suggestion of a split (at the point of inflection at $\sim -7.0$ km s$^{-1}$) was obvious in all the scans. Due to a larger thermal broadening than the other two species, the profiles of H$\alpha$ (Fig. 1c) did not show any split. All these profiles in the central region are fitted to a two-component Gaussian (Anandarao & Rao 1986) and the resultant best fits obtained are shown in Fig. 1(a)–(c). In Table 1, we give expansion velocities obtained in the central region of NGC 2346 obtained in the different lines from the

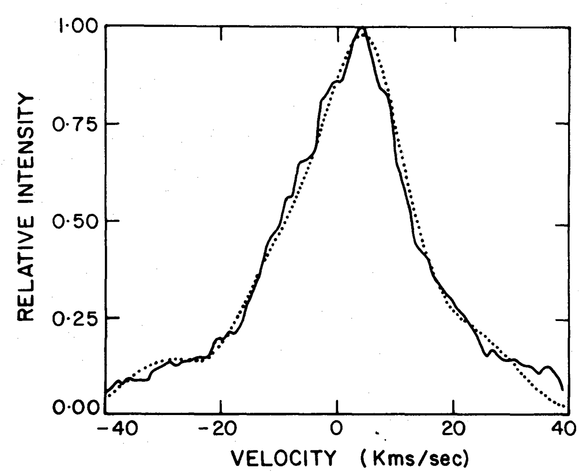


**Figure 2.** The observed [O III] 5007 Å line profile (indicated by the continuous line) from NGC 2346 at a position 10 arcsec away from the centre and in the NE lobe. The observed profile has been fitted by a four-component Gaussian which is indicated by the dotted line.

**Table 1.** Emission line parameters for NGC 2346.

| Emission line | FWHM of first Gaussian (km s$^{-1}$) | Relative intensity of first Gaussian | FWHM of second Gaussian (km s$^{-1}$) | Relative intensity of second Gaussian | Expansion velocity (km s$^{-1}$) |
|---|---|---|---|---|---|
| [O III] 5007 Å | 15.67 | 1.00 | 11.74 | 0.66 | 8.0±1.0 |
| H$\alpha$ 6563 Å | 34.7 | 0.82 | 36.41 | 1.00 | 10.0±1.0 |
| [N II] 6583 Å | 28.97 | 0.77 | 26.04 | 1.00 | 11.0±1.0 |

Gaussian decomposition. The widths of the individual Gaussians and their relative intensities are also given in the table. The [O III] line profile in position 2 could not be simulated by a two-Gaussian fit especially at the wings and had to be fitted by a four-component Gaussian. This profile shows the presence of two weak components at the wings separated by 53 km $s^{-1}$ and two stronger central components separated by 15 km $s^{-1}$.

## 3 Discussion

The expansion velocities in the line-of-sight obtained in the central region of NGC 2346 are $8\pm1$ km $s^{-1}$ in the [O III] line and $11\pm1$ km $s^{-1}$ in the [N II] line. In comparison, from Fig. 2(b) in Walsh's (1983) paper one can infer an expansion velocity of $14\pm4$ km $s^{-1}$ (in the [N II] line) near the central star. For the [N II] line (within the observational errors) this value tallies well with our results. Our observations show that this nebula falls into the category of nebulae whose expansion velocities (in the line-of-sight) deviate considerably from the usually quoted figure of 20 km $s^{-1}$ for a typical planetary nebula. The true expansion velocities along any principal axis with respect to the centre of the nebula, however, depend upon how the nebula is oriented to the line-of-sight. We shall come back to this aspect later in this paper while discussing the morphology of the nebula. Assuming that the [N II] line arises from the outer regions of the nebula and the [O III] line from the inner regions, the difference found from our observations in the expansion velocities in these two lines would imply an outward gradient in $V_{exp}$. However, this outward gradient in expansion velocity seems to be true only for the central region of the nebula and along the line-of-sight. For the outer regions, i.e. in the hour-glass shaped SW and NE lobes, the [N II] radial velocity observations of Walsh (1983) indicate that the expansion velocity decreases with radial distance. This point is re-examined later when the morphological model of NGC 2346 is discussed.

A rough estimate of ion temperatures was also made using the widths of the H$\alpha$ and [N II] line profiles, following Courtes, Louise & Monnet (1968) and by also incorporating the modifications made in the above method by Dyson & Meaburn (1970). In using this method we have made the following assumptions:

(i) the width (FWHM) of any emission line is made up of essentially two components – the component due to thermal broadening and the non-thermal component (assumed Gaussian) due to macro-turbulence or mass motions. We have found by deconvolving the observed profiles that the instrumental broadening effects are negligible and alter the widths by about 2 km $s^{-1}$;

(ii) the non-thermal component is the same for the H$\alpha$ and [N II] lines which are assumed to originate from the same region in the nebula since the ionization potentials of these two species are almost the same.

However, it cannot be ruled out, that the [N II] line originates from the outer regions while the H$\alpha$ line comes by and large from all over the nebula. Also, there could be small-scale structures present along the line-of-sight and/or in the plane of the nebula within the field of view. Therefore, the uncertainties in determining the ion temperatures using the linewidths may be large except perhaps in the case of observations of high-spatial resolution (Walsh & Meaburn 1987). In spite of these difficulties, the method seems to give reasonably reliable values, comparable with electron temperatures derived from the intensity ratios of forbidden lines. We have obtained an ion temperature (averaged for the red and blue components) of $T=10\,650\pm2950$ K. The error indicated represents the uncertainty in determining the widths of the profiles by the Gaussian-fitting procedure. It may be noted here that Sabbadin (1976) had evaluated the electron temperature to be 14 200 K from the [N II] line ratios. The non-thermal (turbulent) velocities turn out to be almost the same for the blue and the red components, the average value being $16\pm2\,\mathrm{km\,s^{-1}}$.

The radial velocity measurements in the [N II] line by Walsh (1983) reveals two features in NGC 2346:

(i) the profiles are split into distinct red and blue components only south of the central star for slit position A and only north of the central star for slit position C (*cf.* fig. 1 in Walsh 1983). At slit position B splitting of the line occurs almost symmetrically about the central star;

(ii) there is an abrupt change-over in the relative intensities of the blue and red components around the nebular waist in the middle of which the central star is located. In slit position A, the red component is brighter than the blue and the reverse occurs along slit-length C. At slit position B, the red component is more intense south of the waist. Above it a reversal occurs with the blue component being stronger than the red.

The splitting of the [N II] radial velocities all along the length of the nebula in the N–S direction has been explained by Walsh by assuming the nebula to be in the shape of an elongated cavity or tube. The change-over in the brightness of the blueward and the redward components of the [N II] line N and S of the waist has been attributed to a difference in density of the nebular matter along the line-of-sight (since $I\propto N_e^2$ for forbidden and recombination lines). However, the observed features can adequately be explained without recourse to inherent density variations by assuming the nebula to be biconical in form (as its appearance suggests) rather than tubular and by also invoking a particular line-of-sight geometry. It may be relevant to point out here some of the mechanisms which can give rise to bipolar morphology in planetary nebulae viz:

(i) mass ejection from active spots on the central star of the planetary nebula. A bipolar morphology can result, as in the case of NGC 650/1 (Recillas-Cruz & Pismis 1984), if these active spots have magnetic fields associated with them and are located symmetrically on the opposite hemispheres of the star;

(ii) in the case of binary star systems, bipolar structure can be produced efficiently by means of the interaction of the gas released by the outflowing giant with the companion star (Kolesnik & Pilyugin 1986).

However, the above mechanism does not seem feasible in NGC 2346 since it requires that the mass of the companion star should range between 0.1 and $0.4\,M_\odot$ which is not the case in NGC 2346.

In Fig. 3 a sketch of the nebula is presented depicting a possible geometry to explain the observed features outlined in the above paragraph. It is assumed that the polar axis of the nebula is oriented towards the line-of-sight by an angle $\theta$ to the plane of sky (Fig. 3) and that the nebular matter is uniformly distributed in the outwardly expanding and uniformly thick walls of the biconical structure. Then it can be shown that the volume elements of the approaching and receding shells subtended along the line-of-sight per unit solid angle are related by

$$\frac{V_1}{V_2}=\frac{r_b\cos^2(\phi+\theta)}{r_r\cos^2(\phi-\theta)}, \tag{1}$$

where $r_r$ and $r_b$ are the distances from the approaching and receding shells to the observer respectively and $\phi$ is the semi-vertical angle of the conical nebular shell.

The intensity of a forbidden line may be written as (see for example Pottasch 1984)

$$I_{ul}=h\nu_{ul}A_{ul}\int n_u\,dV, \tag{2}$$

where $A_{ul}$ is the rate of radiative transitions from an upper level $u$ of an ion whose density is $n_u$ in a

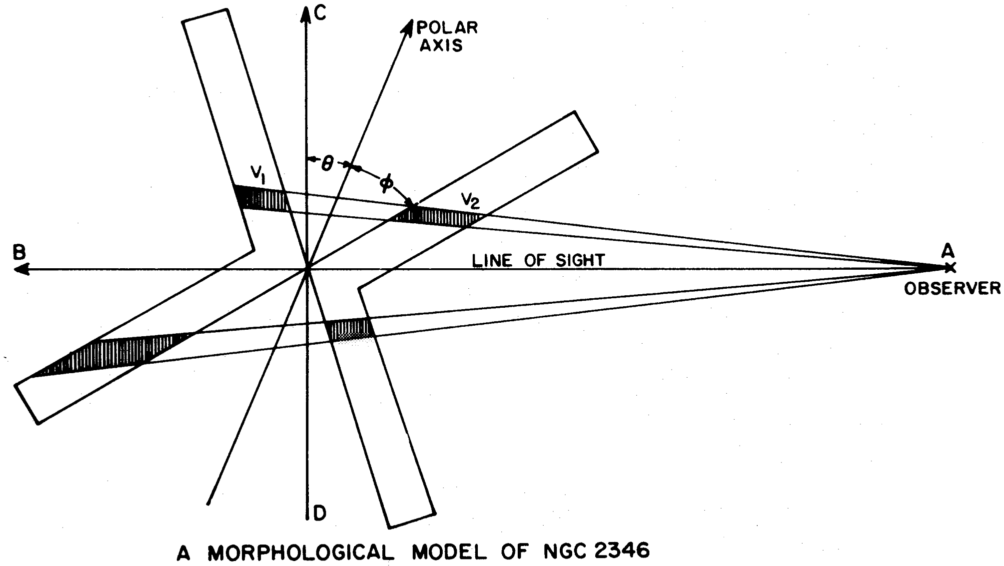


**Figure 3.** A schematic representation of NGC 2346 which is assumed to be biconical in structure (with a semi-vertical angle $\phi$) and having its polar axis tilted (by an angle $\theta$) towards the observer. The above geometry indicates how it is possible to have different intensities from the approaching and receding shells of the nebula due to the different volume elements ($V_1$ and $V_2$) subtended per unit solid angle in the line-of-sight.

volume element $dV$. It can be seen from equation (2) that for the same density but different volume elements the observed intensity will be different. By setting $r_r = r_b$, $\phi = 45°$ and using equation (1) it can be seen that the relative intensities of the blue and red components can vary from 2 to 10 (values compatible with the observations of Walsh 1983), for orientations of the polar axis varying from $\theta = 10°$ to 30°. For $\phi = 30°$, we find that the ratio of intensities of the blue and red components vary between 2 and 4 by changing $\theta$ from 15° to 30°. A tilt of $\theta = 15°$ for $\phi = 45°$ or $\theta = 25°$ for $\phi = 30°$ is required to produce the typical ratio of 3 observed by Walsh.

From our observations of the expansion velocity in the central region of the nebula and using the above mentioned values of $\theta$ one can see that the actual velocities along the polar axis of the nebula range from 20–30 km $s^{-1}$ for the [O III] line and 25–45 km $s^{-1}$ for the [N II] line. For the same values of $\theta$, the true expansion velocity in a direction perpendicular to the polar axis can also be shown to be marginally greater (~1 km $s^{-1}$) than the observed line-of-sight velocities. Further if the polar axis is tilted towards the observer as assumed by us, it can be seen from Fig. 3 that for the northern cone the volume element contributing to the intensity is greater for the blueshifted component than for the redshifted one. In the southern cone the reverse is true with the volume element of the red component being larger than for the blue component. Thus a switch-over of intensity should be found at the waist for slit position B as the observations of Walsh indicate. Also, as the above geometry demands, along slit length A the red component should be brighter in the southern part of the nebula whereas in slit position C the blue component should be brighter than the red as was observed by Walsh. The absence of a secondary component above the waist in position A and below it in position C can be attributed to the tilt of the nebula in the plane of the sky (*cf.* fig. 1 of Walsh 1983) and the positioning of the slit across the nebula. If the flow is outward in the biconical structure, then it can be seen that the northern half of slit length A and the southern half of slit length C are quite close to the edges of the expanding shell. Hence the expansion velocity components will be small along the line-of-sight and be manifested in the absence of line splitting in these regions. Thus it can be seen that the differences in the relative strengths of the approaching and receding components observed in NGC 2346 may very well be explained by the way in which the nebula is oriented with respect to the line-of-sight.

The [N II] velocity map by Walsh also indicates that there exists a tilt to the velocities along the three slit lengths A, B and C. The tilt as can be seen from Walsh (1983, fig. 2) is in the redward direction. If we assume that the velocity of the flow along the walls of the biconical structure increases with distance from the centre, then it is expected from the morphological model proposed above that the blue component of the southern lobe should be relatively more redshifted than the blue component of the northern lobe. That is, the tilt in velocities should be in a blueward direction which is contrary to the observations.

Therefore it appears that there is a decrease in the velocity flow along the nebular walls as one moves away from the nebular centre. Such a decreasing velocity in the outward direction can account for the tilt in the velocities being in the redward direction. This is so because the velocities will be different for two points on the nebula which are located symmetrically at equiangular distance about the central star because these points actually correspond to different radial distances from the centre of the nebula (since the nebula is assumed to be tilted towards the observer). The observations of Walsh, especially in slit position B, indicate that $V_{\mathrm{exp}}$ does not increase with distance. In fact wherever line splitting is clearly indicated, $V_{\mathrm{exp}}$ seems to be constant over a part of the nebula and then shows a marginal decrease as one moves outward. Further the tilt of the velocities towards the redward direction will be accentuated and increased if one considers the nebula to be of a true hour-glass structure with the conical walls curving inwards in the outer regions. Also, if there is a decrease in velocity flow along the walls, then in the outer regions of the nebula the difference in velocity between the blue and red components will be too small to give rise to line splitting into well resolved components. This will account for the merging of the blue and red components in slit position B of Walsh's observations for the outer regions of the nebula.

## 4 Conclusions

The important conclusions of the paper are as follows:

(i) Expansion velocities (line-of-sight) of $8\pm1\ \mathrm{km\,s^{-1}}$ in the [O III] line and $11\pm1\ \mathrm{km\,s^{-1}}$ in the [N II] line are observed in the central region of NGC 2346. An expansion velocity of $7.5\pm1\ \mathrm{km\,s^{-1}}$ is observed in the [O III] line in a position 10 arcsec away from the centre and in the NE lobe of the nebula.

(ii) An ion temperature of $10\,650\pm2950$ K and a turbulent velocity of $16\pm2\ \mathrm{km\,s^{-1}}$ are derived from the widths of the H$\alpha$ and [N II] emission lines.

(iii) A morphological model of the nebula is proposed to understand the spatial variations of the relative intensities of the blue and red components observed by Walsh (1983). According to the model, the observed features can be explained by assuming the nebula to be biconical in shape and tilted towards the line-of-sight.

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