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Spectroscopic investigations of planetary nebulae

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Abstract. The morphologies of three selected asymmetrical planetary nebulae (PNe), namely NGC 4361, NGC 1514 and NGC 246, were studied using spatio-kinematic observations made with an Imaging Fabry-Perot Spectrometer. From the 3D spatio-kinematic models, plaussible nebular formation scenarios were proposed for NGC 4361 and NGC 1514 based on the interacting binary progenitor model. A few parameters regarding the binary, viz. the progenitor's mass and the binary separation, were suggested from this study. The elemental concentration of N and He in the nebulae were used to get some information regarding their progenitors. It is suggested from our study that the binary progenitor hypothesis gives more consistent / explanation of the observed structures of these PNe than the single star hypothesis. The physical condition of a PNe interacting with the ambient interstellar medium has been investigated in NGC 246. Its distorted morphology is attributed to its interaction with the Interstellar Medium (ISM).

1. Introduction

Planetary Nebulae (PNe) are the shells formed by the interaction of the fast wind from the central star with the ejected envelopes of the progenitor stars during their late stages of evolution (Kwok et. al 1978, Kwok 1983). the shells are then ionized by the hot core to give line and continum emissions. The physical mechanism(s) by which the envelopes are ejected play a very essential role in stellar evolution studies, although, they are not yet well understood. It is believed that PNe are expected to retain signatures of the massloss and hence play a crucial role in understanding the underlying physical mechanism.

Most of the PNe show axi-symmetric morphologies with many structural components embedded inside (Balick 1987). These shapes and structural components of PNe provide clues about their origin and evolution. There exist two hypotheses to explain the origin of PNe, namely single star and binary star hypotheses. It is now felt that the binary star hypothesis gives a more natural explanation for many observed PNe structures than the single star hypothesis (Soker 1997, Soker 1998). Further, the initial morphologies of the PNe can be altered significantly during the evolution by their interaction with the ISM (Soker, Borkowsky & Sarazin 1991, Dgani & Soker 1998). Hence the impact of such an interaction on PNe morphologies is important to know for the morphological studies of PNe. The spatio-kinematic approach plays a key role in such studies by the fact that they yield the 3D morphologies of PNe overcoming their aspect related problems, as well as the spatial variation of velocity and density of the matter.

The thesis deals with the morphological study of three selected PNe, namely NGC 4361 (Muthu & Anandarao, 2000), NGC 1514 and NGC 246 (Muthu, Anandarao & Pottasch, 2000). Spatio-kinematic observations were used to give 3D morphological models for these nebulae. Their formation scenarios were given from the interacting binary origin based on the existing theoretical studies on asymmetrical planetary nebulae. The elemental concentration in these nebulae were used to get some clues on their progenitor, and spectrographic observations on NGC 1514 and NGC 246 were used to calculate the elemental abundances which were not available in the literature. The physical conditions of the ISM-interacting PN NGC 246 have been studied from our spatio-kinematic observations with the help of the existing analytical models in this topic. The clumpy structures of the nebulae are explained as the nebular fragmentation caused by instabilities. It is shown that NGC 246 is an example for the distortion of inherent morphologies of PNe by their interaction with ISM.

2. Observations and data analysis

The spatio-kinematic observations were made using imaging Fabry-Perot Spectrometer (IFPS; Seema et al 1992) at 1.2m Gurushikhar IR telescope, which is operated by Physical Research Laboratory, Ahmedabad, India. The data were collected in either spectrographic mode (SPM), where only a few interferograms were recorded, or scanning mode (SCM; Atherton et al. 1982), where the etalon was scanned for one FSR. The emission line profiles were decomposed into multi-Gaussian using a code (Anandarao & Rao 1985) to find the parameters of individual components. The spectrographic observations were made using Intermediate Dispersion Spectrograph (IDS) at 2.3m Issac Newton Telescope (INT) La-Palma. The data was reduced and analysed in the standard procedure using IRAF. Table 1 show the observation log.

3. Results and discussion

3.1 NGC 4361

New spatio-kinematic observations were made on the planetary nebula NGC 4361 in the emission line (OIII) using IFPS in the scanning mode where the etalon was scanned in 16 steps to cover one FSR. The asymmetric structure of most of the profiles was analysed by decomposing into

Table 1. Observation log using IFPS

Source	Date	Mode	Int. Time	Spatial resolution″
NGC 246	Dec'99	SPM	3600 sec	25 x 4
	Dec'96	SPM	5400 sec	25 x 4
NGC 1514	Dec'96	SCM	300 sec	3 x 3
NGC 4361	May'98	SCM	360 sec	5 x 5

two Gaussian components, however, a considerable number of line profiles show triple components underlining the complexity of the nebular kinematics. Fig. 1 shows a few profiles superimposed on the two level iso-intensity contour map.

The central expansion velocity of this nebula is derived to be 27 km/s. Most of the emission line profiles show red or blue asymmetry. The asymmetrical shape of the profiles changes from one type to the other over two well-defined axes at PAs of 45° and 115°, which coincide with the axes of the inner lobes of the nebula. From this we infer that the nebula has a Quadrupolar morphology. The emission line profiles confirm to the morphology of two pairs of bipolar lobes which are surrounded by a nearly spherical and comparatively faint outer shell. The profiles in the outer shell are found to be nearly symmetric. In the projected sky plane these lobes subtend an angle of 70°. We find the red asymmetry profiles are stronger in amplitude than the blue asymmetric profiles.

Using our generalized 2D synthetic emission line profile code, we verify and validate the assumed 3D morphological model. Fig. 1 shows a few such profiles obtained from the code. We find from the code that the pair of lobes which is at a PA of 45° has a angular size of 50″ (end to end) with an inclination angle of ~ 48°. Using the polar velocity of this pair of lobes as ~ 64 km/s, its kinematic age is estimated to be ~ 2,400 - 7,000 yrs for the distance range of 0.66 to 1.92 kpc. The lobe which is situated at a PA of 115° has the angular size of 55″ with an inclination angle of ~ 35°. The polar velocity for this pair is found to be ~ 54 km/s giving a kinematic age range of ~ 3200 - 9300 years. The outer shell (assumed as a spherical shell in the code) has the expansion velocity of 27 km/s and a size of ~ 55″ indicating a kinematic

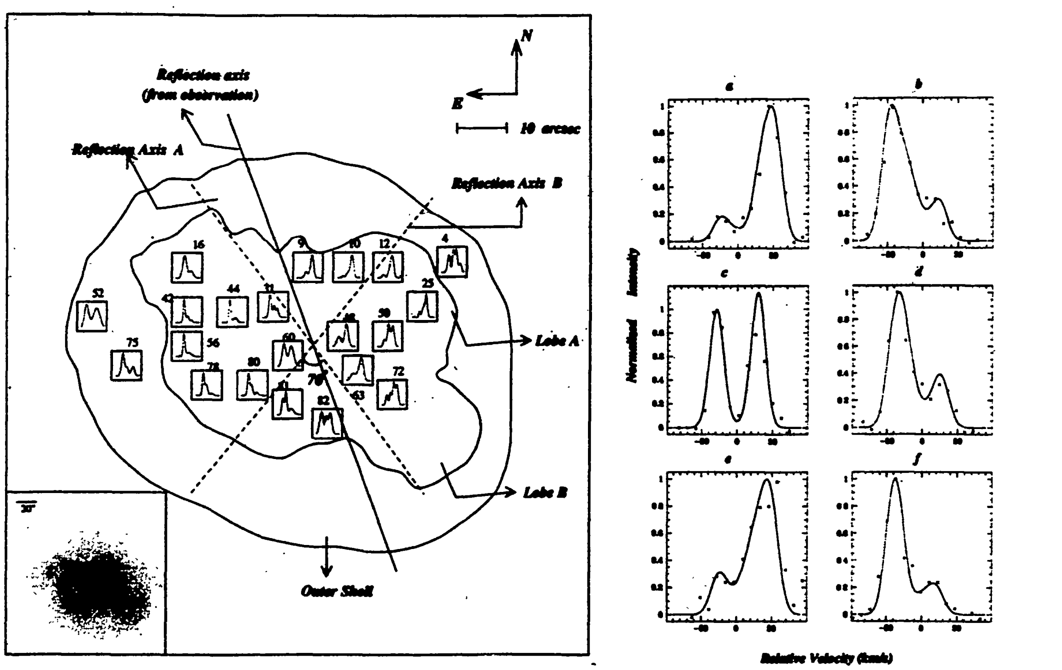

Figure 1. Mosaic of a few typical line profiles of NGC 4361 superimposed on the two level contour of [OIII] filtergram (left figure); Observed lineprofiles (dots) matched with their corresponding code generated profiles (right figure).

age range of ~ 6,100 - 18,000 yrs. Hence the two pairs of lobes were ejected with a time lapse of 700 - 2,200 yrs. The lapse between the ejection of the outer shell and the pairs of lobes is ~ 3,300 - 9,900 yrs.

We propose a formation scenario for this nebula based on the interacting binary progenitor model (Soker 1997). In this model the companion causes an enhanced massloss in the equatorial region (Tout & Eggleton 1988) forming a disk in the orbital plane (Calvet & Peimbert 1983). The coupling between the orbital axis of the binary and the rotation of the progenitor star causes the disk to precess and the nebular ejection at two different phases of this precession results in a Quadrupolar PN (Manchado et al 1996). The precession period of the disk was estimated to have a maximum value of ~ 3,800 - 11,000 yrs and the minimum value of 1,500 - 4,300 yrs. The outer shell represents the progenitor massloss before the disk formation. NGC 4361 was reported to be deficient in heavier elements and is located at relatively high galactic latitude (Torres-Pembert et al. 1990). Further, its central star was estimated to have a mass of $0.55M_{\odot}$ which suggests a low mass progenitor. Generally quadrupolar (and bipolar) planetary nebulae show enhanced chemical evolution, higher concentration towards the galactic center and higher central star mass (Soker 1998). NGC 4361 seems to differ from these general trends.

3.2 NGC 1514

New spatio-kinematic observations on NGC 1514 were obtained in (OIII) line using the IFPS in scanning mode where, the etalon was scanned in 15 steps to cover one FSR. Most of the profiles show asymmetric structure and they were decomposed using two or three Gaussians. We derive an expansion velocity of 25 km/s for this nebula.

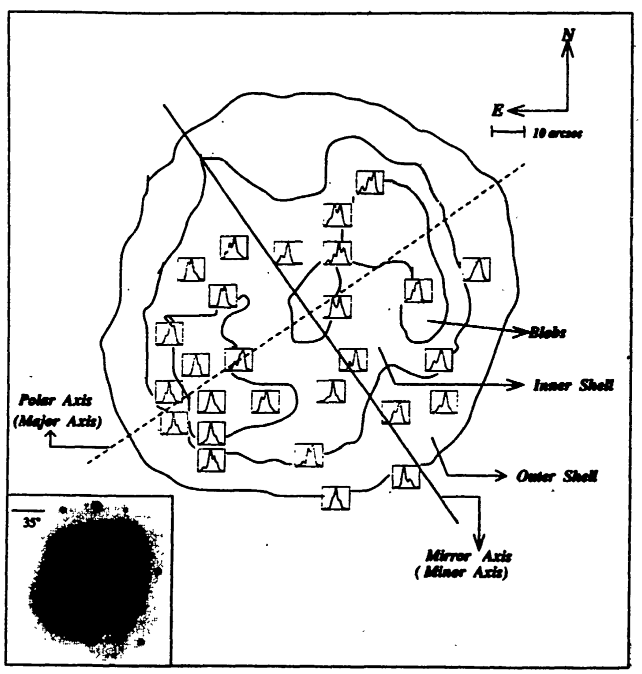

Figure 2. Mosaic of a few typical line profiles of NGC 1514 overimposed on the two level contour of [OIII] filtergram.

NGC 1514 shows a bright inner region which is surrounded by a nearly spherical outer shell. The nebula implies a complex kinematic structure. The line profile asymmetry reverses about an axis as in a mirror reflection (see Fig. 2). From the differential spatial decrement of expansion velocity along the mirror axis and an axis which is perpendicular to that we derive that the shell has an elliptical structure and is tilted with respect to the sky plane. The triple component profiles correspond to the bright blobs which are present along the major axis of the elliptical shell indicating that the blobs are additional components present inside the shell. We find from our results that these blobs are moving faster than the nebular shell.

Using the grating spectrographic observation obtained in the optical region, we derive the extinction coefficient for this nebula from H_α and H_β lines as 0.885 assuming a *case B* condition (Osterbrock 1989). The [OIII] electron temperature was derived as 16,000 K using the [OIII] lines at wavelengths 4363Å, 4959Å and 5007Å. The electron density was estimated as 3,000 cm^{-3} from the [OII] lines at 3726Å and 3729Å. We find the ionic concentration relative to hydrogen for singly ionized helium as 0.11 from the line at 5876Å and for doubly ionized helium as 0.013 from the line at 4686Å. We do not see any signature of nitrogen lines within our detection limit.

From our results, we propose a formation scenario for NGC 1514 in which the Common Envelope had formed when the primary was at its early-AGB stage of evolution and resulted in the nebular ejection. The secondary is reported to be an AIII type star (Chopinet 1963), which suggests a higher mass primary ($\geq 3M_\odot$). We propose that the early formation of a CE terminated the further chemical evolution of the primary (Bond & Livio 1990), leaving the nebula chemically less evolved as to the second dredge-up elements, viz. nitrogen and helium. Assuming a core mass of $0.6M_\odot$, we expect a present separation of 30 to 62 $R_\odot$ for the binary core.

3.3 NGC 246

Using IFPS in the spectrographic mode, new spatio-kinematic observations on the ISM-interacting PN NGC 246 were made in [OIII] line. Two interferograms at two different gap settings of the etalon covering significant portion of the nebula were obtained. The profiles were decomposed into double components and in a few cases triple components were considered. Fig. 3 shows the iso-intensity contour map of NGC 246 where the expansion velocities are superimposed.

The pristine morphology of NGC 246 is considerably distorted by the interaction with ISM. We derive the space motion of this nebula as 86 km/s from the data from *HIPPARCOS* and a radial velocity of -50km/s (Schneider et. al 1983). From our spatio-kinematic observations, shell deceleration in the leading section was detected (see Fig. 3). We explain our results as well as the clumpy structure seen in the leading edge in terms of the nebular interaction with the ISM. The observed clumpy nature is attributed to the shell fragmentation by the Rayleigh-Taylor (dominant in the nebular front) and Kelvin-Helmholtz (dominant in the nebular downstream) in-stabilities (Dgani & Soker 1998). Using an (adiabatic) analytical model suggested by Soker, Borkowski & Sarazin (1991) and the results of our kinematic observations, we estimate a few parameters on the physical conditions of this nebula. The distance to the nebula is uncertain and has a value between 500 - 600 pc (Acker et. al, 1992; Pottasch, 1996). Hence the estimated quantities are reported corresponding to the distance range. The stopping timescale of the nebular shell is estimated as ~ 12,000 - 16,000 yrs for the nebular kinematic age of 7,200 - 8,800 yrs. For an average electron density of the leading section of 80 cm^{-3}, the expected ISM density surrounding the nebula is estimated to be ~ 2.8 - 1.6 cm^{-3}. This value is unusually high compared to the average ISM density at the galactic latitude of the nebula. The difference in the radii of the leading and trailing sections was estimated to be 0.23 - 0.1 times the radius of the trailing section. The time scale required for fragmenting the shell by RT instability is found to be ~ 11,000 - 29,000 years. We find the fragmentation time for the KH instability as ~ 9,300 years. We conclude by comparing the stopping and the fragmentation time scales with the kinematic age of the nebula that the nebular shell is neither arrested nor has the RT instability grown fully to completely fragment the nebular shell in the front. However, the growth time of KH instability is comparable to the nebular age indicating that it has completely fragmented the nebular downstream.

The (OIII) electron temperature was derived from the grating spectrographic data for the leading and trailing sections separately. We found that the electron temperature of the leading half (2.4×10^4K) is 1.54 times larger than that of the trailing half (1.56×10^4K). We attribute this effect to the compression of the leading edge by the ISM ram pressure by which the leading edge was heated up. We estimate the difference in the temperature theoretically and find that it is in good agreement with the value derived from the spectra. This is the first observational evidence of such a difference in temperature in the leading and the trailing halves.

From the grating spectrographic observations, we calculate the extinction coefficient as 0.265 assuming a *Case B* condition. The elemental concentrations for helium ions relative to hydrogen was estimated using an emperical relation. The relative abundance of singly ionized helium has been calculated from the line intensity at 5876Å to be 0.03; and that of doubly

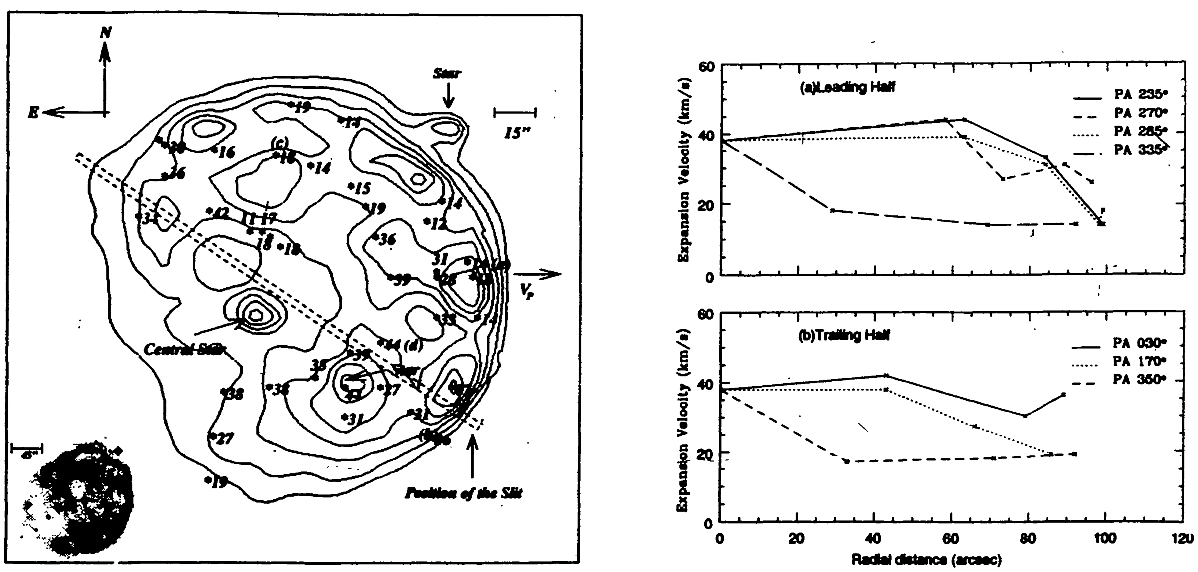

Figure 3. Expansion velocity map (values in km/s) of NGC 246 superimposed on the two level iso-intensity contour of the [OIII] filtergram (left figure); Variation of the expansion velocity with radial distance in the leading (a) and trailing (b) halves (right figure).

ionized helium from the line intensity at 4686Å to be 0.1. Thus our results show that most of the helium is in the doubly ionized state implying that NGC 246 is a high ionization nebula. We do not see any nitrogen lines within our detection limit and this is consistent with the result that the nebula is in a high ionization stage.

4. Future Plans

Most of the PNe are ionization bounded and there exist a relatively cold (molecular) matter around the ionized nebular (circum-nebular envelope; Bachiller et. al. 1993; Huggins et. al. 1996). It is important to study this region to know whether the onset of bipolarity can precede the production of PNe (Kastner & Weintraub 1994; 1995; Trummell, Dinerstein & Goodrich 1994). One of the best methods to trace these regions is to observe them in the 2.122μm vibrational line of H_2 (v = 1-0 S(1)) and the CO lines at 2.6 mm. A detailed study of these envelopes (imaging and the kinematics) will offer some insight into the origin and structure of PNe. Natta & Hollenbach (1998) theoretically find that the evolution of the molecular envelope passes through three phases. The presence and the duration of these phases depend on the central star mass which is the main parameter that controls the PN evolution. Our future plan is to study these envelopes in the near-infrared and mm regions.

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