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Imaging Fabry-Perot spectrometric studies of velocity fields in gaseous nebulae

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Abstract. In order to study the spatio-kinematics of extended gaseous nebulae such as the HII regions associated with giant molecular clouds and planetary nebulae, we had designed and built an Imaging Fabry-Perot Spectrometer for the 1.2m Mt Abu Telescope. We describe here some of the significant scientific results that came out of these studies in the past one decade at Mt Abu.

Keywords : Imaging Fabry-Perot spectrometer; HII regions; Planetary nebulae; Kinematics

1. Introduction

Gaseous Nebulae that are discussed in this article are of two types(Osterbrock 1989): (i) the HII regions associated with massive star formation in molecular clouds(Yorke 1986; Franco, Tenorio-Tagle and Bodenheimer 1990); and (ii) the planetary nebulae that represent the late stages of intermediate mass stars(Pottasch 1984; Kwok 2000). We had taken up a project to investigate the velocity field structure of galactic nebulae in order to understand their spatio-kinematics and possibly the dynamics. For velocity field studies, the Fabry-Perot Spectrometer(FPS) is proved to be a very powerful tool as it has the highest throughput($R\Omega$, where R is the resolving power and Ω is the solid angle subtended by the etalon) (see for a review, Desai 1984). Due to this inherent nature, the FPS can be gainfully used even with moderate-sized telescopes such as the Mt Abu 1.2m telescope. Nearly seeing-limited spatial resolution may be achieved with proper design of the instrument. Moderate spectral resolutions that correspond to velocity resolutions of $\sim$ 10 km/s are adequate to meet a number of scientific goals. With this motivation we

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had designed and built an Imaging Fabry-Perot Spectrometer(IFPS) to carry out these studies at Mt. Abu (Seema et al., 1992). We briefly describe here some of the significant results that we had obtained so far on the two types of gaseous nebulae mentioned above, namely the galactic HII regions and planetary nebulae.

2. The PRL imaging Fabry-Perot spectrometer

The PRL IFPS utilizes piezo-electric servo-controlled etalons that have highest stability and scanning accuracy(Atherton etal 1982). An imaging photon-counting detector(IPD) is used to record the interferograms. IFPS had been designed for obtaining kinematic information on regions of extent 2' x 2' at nearly seeing-limited spatial resolution of about 2-3 arc sec. Currently the PRL IFPS system covers a spectral range of 4000-8000 Å in the visible range and 1.65 - 2.5 μm in the near-infrared (Anandarao etal. 2000) with several etalons of different velocity resolutions, the minimum being $\leq$ 10 km/s. All the observations reported here were made during 1995-2000 at the Cassegrain focus of the 1.2 m telescope at Mt. Abu.

3. Champagne flow and turbulence in the Lagoon nebula

Kinematic study of an HII region is important to understand the mechanisms responsible for the expansion of the region and turbulence characteristics. The aim of our study was to see if there exist champagne type large flows of expansion in the region and also to characterize turbulence if present(Joncas 1995). Both the champagne flow and the turbulence are important for controlling the on-going and future star formation in the cloud(Lizano et al., 2003).

The Lagoon Nebula (M8, NGC 6523) is one of the closest and the brightest galactic HII regions situated at a distance of 1.5 kpc. At the centre of the optical nebulosity of this object there exists an Hourglass (HG) structure that has the highest surface brightness in the visible (Lynds and O'Neil 1982). The source of ionizing photons is the O7 V type star called Herschel 36. Only limited kinematical observations existed on the Hourglass region prior to our work. Our observations were made during April 1995 at Mt. Abu using the IFPS. The emission lines [OIII] λ 5007Åand [NII]λ 6584Åwere chosen to map the velocity fields in the HG region of M8 covering about 2'$\times$2'. A single interferogram was obtained in [NII] line and hence the spatial sampling of line profiles was coarse (5" at the centre and 25 arcsec at the edges of the interferogram). In the case of [OIII] line wavelength scanning was done and the spatial sampling was much better at 2-3 arcsec.

The [NII] line profiles were found to be asymmetric at many positions indicating multiple components and considerable expansion velocity of up to 30-50 km/s. Random motions due to turbulence of widths up to 15 km/s were noticed. Our results showed that there exists a champagne flow in the HII region that has an estimated age of ~ 5 x 10^4 yrs (for details, Chakraborty and Anandarao 1997).

The [OIII] line observations also showed large velocities like in the case of [NII] lines and confirmed a champagne flow model. The structure function that characterizes the turbulence showed a power law index of 0.46 with an indication of steepening at larger scale sizes beyond 0.12 pc (Chakraborty and Anandarao 1999). The steepening may be attributed to the dissipation of a shock wave passing through the region (Joncas 1999). These results indicate possibilities of slowing down the star formation rate due to the disruption of the cloud by the champagne flow and turbulence.

The future observational efforts should include studying turbulence at as small spatial scales as possible and should include density structure along with velocity structure.

4. Spatio-kinematic studies of planetary nebulae

Spatio-kinematic observations of Planetary Nebulae(PNe) are very important to investigate the mass loss mechanisms and shaping of the PNe. There exist very limited published data on spatially resolved kinematics of PNe (Balick and Frank 2002). We had selected three PNe for studies using the IFPS. Each one is unique in its own right.

4.1 Kinematic evidence of interaction of NGC 246 with interstellar medium

PNe with large proper motions may in principle have a sufficient ram pressure to interact with the surrounding interstellar matter (ISM) that has larger density than normal (Soker, Borkowski and Sarazin 1991). One of the most conspicuous visible effects caused by this interaction is the displacement of the central star from the centre of the nebula, because the leading edge gets decelerated as it pushes the ISM. Kinematic observations of such PNe are very sparse in the literature.

NGC 246 is one of the best examples of PNe that show noticeable pathologies of interaction (Soker, Borkowski and Sarazin 1991). Images of this nebula show an inhomogeneous density structure possibly caused by the ISM interaction. We (Muthu, Anandarao and Pottasch 2000) studied NGC 246 using the IFPS in the [OIII] 5007Åline. Only one single interferogram was obtained on this rather faint nebula.

A direct kinematic effect of the interaction may be seen in the leading edge that should be decelerated by the ISM preferentially in comparison to the trailing edge. Such a difference between the two sides was indeed observed in our study; the leading half showing rapidly decreasing velocity of expansion V_{exp} compared to the near-constant trend that is seen in the trailing side. This was the first time that a kinematic effect of the interaction with ISM was observed. The ISM interaction may lead in principle to differences in the electron temperature and density in the leading and trailing halves of the nebula. We also noticed a preferential heating of the leading edge in comparison to the trailing edge based on the electron temperature derived from the [OIII] line ratio. Such an effect in temperature had not been detected prior to the work detailed below.

4.2 Detection of quadrupolar morphology in NGC 4361

The Planetary Nebula NGC 4361 was classified by Chu, Jacoby and Arendt (1987) as a Multiple Shell PN having irregular structures in the surrounding shell. The nearly spherical shell is relatively fainter than the inner regions of the nebula. Recently Vazquez etal.(1999) have proposed a bipolar morphology for this nebula from the overall structure of the line profiles obtained using echelle spectrograph. Our (Muthu and Anandarao 2001) IFPS observations(in the [OIII] line), encompassing nearly the entire visible part of the nebula, suggests the presence of two reflection axes about which the line profiles reverse their asymmetric structure as shown in Fig. 1. The most natural interpretation for the presence of such two axes of symmetry is to invoke a quadrupolar structure for the nebula. The observed line profiles of NGC 4361 could be successfully reproduced by model computations assuming a quadrupolar structure for the nebula. Multipolar PNe are a rare species among PNe; NGC 4361 is only the seventh QPNe to have been detected.

Quadrupolar PNe(QPNe) can be formed from an interacting binary progenitor as suggested by Manchado, Stanghellini and Guerrero (1996). The secondary of a binary system can spin up the primary by its tidal force, enhancing the mass-loss rate in the equatorial plane and forming a disk around the waist. The tidal effect will be significant when the mass of the primary (M_p) is comparable to the mass of the secondary (M_s) with the separation less than 30 AU, during the primary's AGB stage (Soker 1997). The subsequent mass ejection from the progenitor in the presence of a disk will produce a bipolar planetary. Additionally, if the disk precesses around the rotational axis of the primary and if a second mass ejection occurs during the precession, then a QPN will result (Manchado, Stanghellini and Guerrero 1996). The precession of the disk might be produced by the coupling of the orbital angular momentum of the binary with the rotational angular momentum of the progenitor star in the system. The maximum precession period for the case of NGC 4361 was estimated to be in the range of $T_{max} \sim 3800$ - 10900 yrs.

We have also shown that the interaction of the fast moving lobes with the surrounding shell with a relative velocity of 27 km/s yields a temperature increment of 5000 K. This is probably the first time that compression ionization is suggested for PN that is otherwise known to be photoionized.

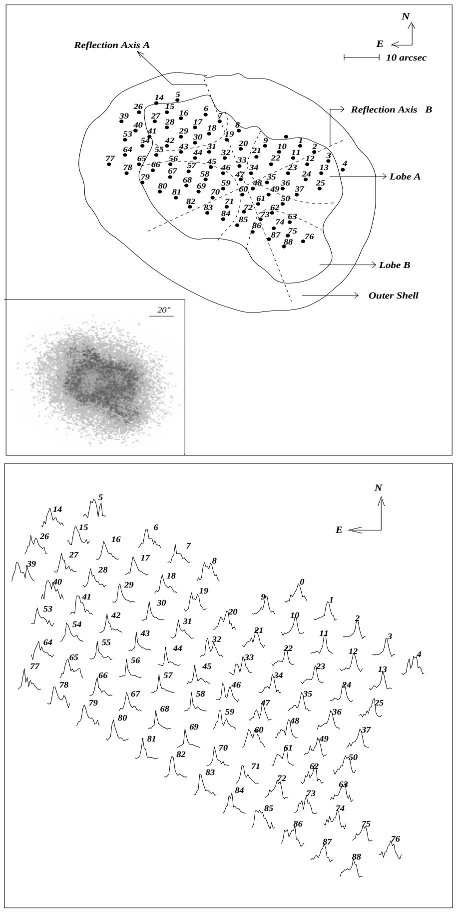

Figure 1. Contour outlines of NGC 4361 based on the [OIII] line Fabry-Perot interferograms (shown in the inset of the top figure). Velocity profile map is shown in the bottom part of the figure. The numbers correspond to profiles (from Muthu and Anandarao 2001).

4.3 Common envelope ejection in NGC 1514

The Planetary Nebula NGC 1514 was identified as a double shell PN by Chu, Jacoby and Arendt (1987). The central star of this planetary is suspected to be a close binary nucleus of period 0.41 day. We (Muthu and Anandarao 2003) have made IFPS observations (in the [OIII] 5007Åline) on this nebula at a near seeing-limited spatial resolution. Our results show that the negative radial gradient of the expansion velocity in the inner shell varies with direction(anisotropic). In a spherical shell the radial variation of V_{exp} should be the same in any direction. But, in the case of an ellipsoidal shell the projection effect renders the gradient of V_{exp} steeper along the minor axis than along the major axis and

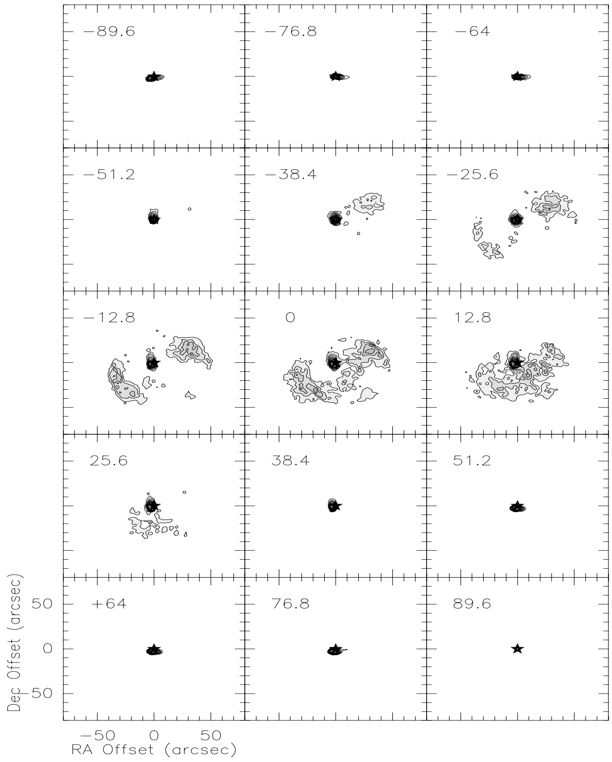

Figure 2. IFPS Velocity Channel Maps in [OIII] line in NGC 1514. The brightening of the two bipolar lobes can be seen in the channel with the relative velocity -12.8 km/s (from Muthu and Anandarao 2003).

this effect changes gradually in directions between the two axes. Our results therefore suggest that the inner shell is an ellipsoidal shell. We conclude that the nebula has three basic structures: the faint outer shell, the inner shell and the bright blobs or bipolar flows.

Fig 2 shows iso-intensity contour maps of the nebula at different velocity frames (central velocity is taken as 0 km/s). The frames correspond to different step positions in a sequence of positive and negative radial velocities with reference to the central frame where the maximum intensity is observed. One can notice a reasonably clear indication of the existence of the two blobs oriented along the polar direction. Our model proves that the PN has been formed from a common envelope in a binary system, when the primary was in its early-AGB stage of evolution. Soker (1997) discussed the possibility of formation of polar blobs or jets by the companion's mass transfer to the progenitor, at the end of the CE phase. These blobs can be poorly collimated due to the possible large size or even the absence of an equatorial disk. It may be conjectured that the polar blobs of NGC 1514 could have formed in a similar scenario. From theoretical considerations, we had estimated final separation between the binary components to be 16-36 $R_\odot$ and an orbital period of 4-9 days.

In future we intend to take up the kinematic study of young and proto-PNe in both ionized and neutral atomic and molecular species that form beyond the photo-dissociation regions.

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