The bipolarity of the highest Galactic latitude planetary nebula, LoTr 5 (PN G339.9+88.4), around IN Com

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Accepted 2003 October 21. Received 2003 October 20; in original form 2003 July 8

ABSTRACT

High-resolution, spatially resolved, long-slit profiles of the [O III] 5007-Å emission line of the highest Galactic latitude planetary nebula, LoTr 5, have been obtained with the Manchester Echelle Spectrometer (MES-SPM) on the San Pedro Martir (SPM) 2.1-m telescope. These are compared with a deep narrow-band [O III] 5007-Å mosaic image obtained with the same system.

This faint nebula, at a distance of $\geq 500$ pc from the Galactic plane, is found to be expanding asymmetrically. Some form of bipolar structure is suggested by modelling the position–velocity arrays of line profiles and the new [O III] 5007-Å image. Interestingly, the modelled bipolar axis is nearly perpendicular to the orbital plane of the IN Com binary system; this supports the theories which predict that binary systems play a part in shaping the outflow.

Evidence for interaction of the envelope of LoTr 5 with its local interstellar medium is also considered.

Key words: line: profiles – stars: individual: IN Com – ISM: kinematics and dynamics – planetary nebulae: individual: LoTr 5.

1 INTRODUCTION

The faint planetary nebula (PN) LoTr 5 (PN G339.9+88.4) was discovered by Longmore & Tritton (1980) and is the highest Galactic latitude PN known. Its $\sim 500$ arcsec diameter envelope (Brosch & Hoffman 1999, who also saw some evidence for bipolarity) emits predominantly in the [O III] 5007-Å emission line, for it is radiatively ionized by the hot ($150 000$ K) separated binary companion (Feibelman & Kaler 1983) of the cool ($5230$ K) G5 III, $m_v = 8.8$ star (HD 112313, SAO 82570, HIP 63087) in the central system, IN Com (Jasniewicz et al. 1996). In fact, the X-ray observations of Guerrero, Chu & Gruendl (2000) indicate that this is the hottest companion star yet found in any PN. It has even been suggested that IN Com is a triple system where the G5 III star itself has a low-mass M5 close binary companion (Malasan, Yamasaki & Kondo 1991).

Bond, Pollacco & Webbink (2003) identify the central stellar system, IN Com, as an 'Abell 35'-type PN nucleus where a rapidly rotating ($60$ km s$^{-1}$ – see Jasniewicz et al. 1996) late-type giant is possibly spun up by accretion from the well-separated but very hot companion. Gatti et al. (1998) give the separation of the binary components of Abell 35 as 18 au.

Knowledge of the distance to LoTr 5 is particularly crucial because of its high Galactic latitude (i.e. nearly overhead in the Galactic plane). If more than a few hundred parsecs above the plane, it will be expanding into the tenuous Galactic halo and there is unlikely to be significant interaction with the ambient interstellar medium (Tweedy & Kwitter 1996, see also Section 3.3). The Hipparcos parallax, $\pi = (0.83 \pm 1.17) \times 10^{-3}$ arcsec, of the central system IN Com (Acker et al. 1998) now gives a very firm lower limit to the distance of LoTr 5 of 0.5 kpc. In fact, they adopt this as the most likely distance in view of the marginal $\pi$ detection ($\sigma \pi / \pi = 1.4$). A distance of 500 pc is consistent with the estimated distance for the central G5 III star by Longmore & Tritton (1980), but in stark contrast to a distance of 6.9 kpc derived from the statistical properties of PN envelopes given by Cahn, Kaler & Stangellini (1992). The latter distance is almost certainly a gross over-estimation (Jasniewicz et al. 1996). Acker et al. (1998) give the proper motions (PMs) of the central system of LoTr 5 as $\mu_{\alpha} = (-24.54 \pm 1.08) \times 10^{-3}$ arcsec yr$^{-1}$ and $\mu_{\delta} = (0.05 \pm 0.88) \times 10^{-3}$ arcsec yr$^{-1}$.

In the present paper, a mosaic of images of unprecedented sensitivity in the light of the [O III] 5007-Å line is presented of the faint envelope of LoTr 5. This mosaic has also been combined with a series of long-slit spectra which contain spatially resolved line profiles over the nebular area. Previously, a single [O III] 5007-Å profile obtained with a scanning Fabry–Perot interferometer (Weinberger 1989; Hippelein & Weinberger 1990) over the nebular centre had indicated an expansion velocity $V_{\text{exp}} = 27$ km s$^{-1}$ under the assumption of simple spherical expansion of the nebular envelope.

As a consequence of these new observations, a better understanding of the kinematics and morphology of the PN envelope has now...
Figure 1. Positive and negative grey-scale representations of the mosaic of seven [O III] 5007-Å images of LoTr 5.
become possible. LoTr 5 is shown to be far from a simple spherical expanding shell as suggested by the earlier images (Longmore & Tritton 1980). Some implications for the structure of the unusual central stellar system have also emerged.

2 OBSERVATIONS AND RESULTS

The present observations were made with the Manchester Echelle Spectrometer (MES-SPM – see Meaburn et al. 1984, 2003) combined with the 2.1-m San Pedro Martir (SPM) telescope. A SITE3 CCD was the detector with 1024×1024 24-µm pixels, although 2×2 binning was employed throughout the observations.

2.1 Imagery

MES-SPM has a limited imaging capability with a plane mirror isolating the echelle grating and a clear area (here 5.12×5.12 arcmin²) replacing the spectrometer slit. With this arrangement, seven 600-s integrations on separate pointing centres around the central stellar system IN Com were obtained through a 60-Å bandwidth filter centred on [O III] 5007 Å. Grey-scale representations of this mosaic of images are shown in Fig. 1. These have been merged using the Starlink FIGARO and KAPP A software packages. All spectra were calibrated in heliocentric radial velocity ($V_{\text{hel}}$) to ±3 km s⁻¹ accuracy against spectra of a thorium/argon lamp.

Three integrations, two of 1800-s duration and one of 900 s, were obtained in 2001 May with the slit orientated east–west. Adjacent slit centres were displaced by 3 arcmin to permit sufficient overlap yet cover the full east–west extent of LoTr 5. This line of measurements is marked as path 1 in Fig. 2, and the negative grey-scale representation of the resultant merged position–velocity (pv) array of [O III] 5007 Å profiles is shown in Fig. 3. The longer (3600 s) integrations obtained in 2002 May with the slit orientated north–south were along the paths 2–5 shown in Fig. 2. The north–south line (path 4) of measurements through IN Com is for three integrations, i.e. one centred on IN Com, one displaced 3 arcmin north and one similarly south. The negative grey-scale pv arrays from these positions are shown in Figs 4(a)–(d). Note that the overlap regions of this mosaicicked pv array had equivalent integrations of 5400 s, giving a far superior signal-to-noise ratio than for the east–west array shown in Fig. 3.

As triple radial velocity components can be seen clearly in the north–south pv arrays for paths 2–4 [Figs 4(a)–(c)], these have been simulated in Figs 5(a)–(c) along the respective paths by the addition of up to three Gaussians. The parameters of the Gaussians are listed in Table 1.

3 DISCUSSION

3.1 Morphology and kinematics

The image in Fig. 1 shows that LoTr 5 is significantly non-spherical. In fact there appear to be two major structures displaced from each other as indicated by the dashed lines in Fig. 2. IN Com now is at the link package CCDPACK. For the astrometry of Figs 1 and 2, GAIA was used along with the United States Naval Observatory catalogue.

2.2 Long-slit spectroscopy

Spatially resolved, long-slit line profiles at high spectral resolution were obtained with the MES–SPM. This spectrometer has no cross-dispersion. For the present observations, a filter of 60-Å bandwidth was used to isolate the 114th echelle order containing the [O III] 5007-Å nebular emission line.

The 512 increments, each 0.60 arcsec long, give a total projected slit length of 5.12 arcmin on the sky. ‘Seeing’ was always ≤1 arcsec during these observations. A 150 µm wide (=12 km s⁻¹ and 1.9 arcsec) single slit was used.

The data were bias-corrected, cleaned etc. in the usual way using the Starlink FIGARO and KAPP A software packages. All spectra were calibrated in heliocentric radial velocity ($V_{\text{hel}}$) to ±3 km s⁻¹ accuracy against spectra of a thorium/argon lamp.
Figure 4. Negative grey-scale representations of the north–south \([\text{O} \text{ III}]\) 5007-Å pv arrays as shown in Fig. 2 positioned at right ascensions of (a) path 2 at 12\textsuperscript{h}55\textsuperscript{m}42\textsuperscript{s}9, (b) path 3 at 12\textsuperscript{h}55\textsuperscript{m}38\textsuperscript{s}7, (c) path 4 at 12\textsuperscript{h}55\textsuperscript{m}33\textsuperscript{s}7 and (d) path 5 at 12\textsuperscript{h}55\textsuperscript{m}20\textsuperscript{s}9. The three overlapping positions along path 4 [shown in (c)] are centred on IN Com (HD 112313) and have been mosaicked into one continuous pv array. The heliocentric radial velocity \((V_{\text{HEL}})\) range of all pv arrays is \(\pm 200\ \text{km s}^{-1}\).
Figure 5. Profiles extracted from the north–south pv arrays (a) at an RA of 12°55′42″ for path 2 in Fig. 2, (b) at an RA of 12°55′38″ for path 3 in Fig. 2, and (c) at an RA of 12°55′33″ for path 4 in Fig. 2. The declination range over which each profile was extracted is shown. Up to three Gaussian profiles have been fitted to each spectrum and their properties are summarized in Table 1.
The morphology of LoTr 5 as shown in Fig. 1 and the pv arrays of [O III] 5007–Å profiles in Figs 3 and 4 could suggest some form of bipolar structure with the bipolar axis inclined at around 17° to the sight-line as shown in Figs 6 and 7. This possibility has been modelled using the XSHAPE code of Steffen, Holloway & Pedlar (1996) to predict in Fig. 6 the pv arrays along paths 1–5. The model produced is a bipolar shell with semi-major and semiminor axes of 390 and 100 arcsec respectively. This is viewed with the polar axis at a position angle of 55° and inclined at 17° to the line of sight. The south-west lobe is pointing towards the observer. Expansion of the model is radial from the centre and follows a $v \propto r$ law. Slit positions were identical to those observed, and the synthetic pv arrays were convolved to the observed seeing conditions and the instrumental velocity resolution of the MES-SPM. The parameters of the model were continually adjusted until the best agreement between both observed and synthetic images and pv arrays was reached. There are some aspects of the predicted pv arrays that suggest that this simple bipolar model is reasonably correct; the triple radial velocity components in the south of the path 4 pv array are reproduced. Many areas of enhanced emission throughout the observed pv arrays are also reproduced, such as those in the west of the east–west pv array (path 1) and in the north of the path 2 pv array. The broadening of the profiles in the northern half of path 5 is also a prediction of the XSHAPE modelling.

However, the limited knowledge of the morphology of the bipolar structure leads to some discrepancies in detail between the model and observed pv arrays: the edges of constituent shells would appear to be too thin, leading to regions in the predicted pv arrays that are more well-defined than in the observed ones. There is certainly some evidence for thick-shell expansion in the latter, since the observed profiles are significantly wider than the instrumental broadening of 12 km s$^{-1}$. The triple feature in the south of the observed pv array along path 4 seems to extend (albeit very faintly) north of that in the model pv array. The Gaussian fitting (Fig. 5c and Table 1) for declination 25°52'09"–25°53'31" also clearly shows that the central velocity component (at the centre of path 4) is redshifted with respect to the central star. This is very difficult to produce with a simple bipolar model, because even if the ‘waist’ of the structure were to come closer to the central star, the central velocity component produced by this would pass through the systemic velocity at the position of the central star. The brighter portion of the third component is accurately reproduced by a narrow waist in the model, and it may be that the portion extending towards the central star in the pv arrays is due to another region of emission in the shell, possibly a double-shell structure near the poles. Bipolarity is generally expected in type I PNe, therefore it is somewhat surprising to find this characteristic in a high-latitude PN with a low-mass progenitor. In this regard it is interesting that Vázquez et al. (1999) have also found a bipolar outflow in the Population II PN NGC 4361, which is $\sim$830 pc from the Galactic plane. Contrary to the case of LoTr 5, there is no reported evidence of a binary central system in NGC 4361. However, the influence of binary cores may explain the presence of axisymmetric outflows in this type of nebula.

Soker & Rappaport (2000) have suggested that bipolar outflows can result from the slow wind of an asymptotic giant branch (AGB) star being blown by the fast wind of its separated white dwarf binary companion, in which case the outflow is perpendicular to the binary orbital plane. If something similar has happened within IN Com to form LoTr 5 then the model in Fig. 7 would suggest that the axis of the binary orbits is similarly at an inclination, $i \approx 17^\circ$, to the sight-line. This is just within the $9^\circ \lesssim i \lesssim 17^\circ$ range suggested by Jasniiewicz, Acker & Duquennoy (1987), which is derived from measuring the radial velocity variations of the central IN Com system.

Considering the binary core in LoTr 5, it is also likely that nebular shaping was influenced by ejection of the common

### Table 1. Properties of the Gaussian profiles fitted to the spectra in Figs 5(a)–(c).

| Dec. Range | Gaussian 1 | Gaussian 2 | Gaussian 3 |
|------------|------------|------------|------------|
| Dec.1      | Dec.2      | Centre     | FWHM       | Centre     | FWHM       | Centre     | FWHM       |
| 54°35'     | 55°55'     | 65.6       | 20.5       | 15.3       |
| 53°14'     | 54°34'     | 24.5       | 25.0       | 21.7       |
| 51°54'     | 53°14'     | -3.5       | 5.4        | 31.8       |
| 50°33'     | 51°53'     | -22.8      | 2.0        | 45.5       |

Path 2

| 54°25'     | 55°45'     | -23.6      | 42.7       | -19.9      |
| 53°04'     | 54°24'     | -35.4      | 24.8       | 21.9       |
| 51°43'     | 53°04'     | -31.6      | 28.9       | 17.4       |
| 50°23'     | 51°43'     | -18.7      | 41.0       | 35.5       |

Path 3

| 56°13'     | 57°34'     | -18.6      | 37.8       | 12.6       |
| 54°52'     | 56°13'     | 21.7       | 46.9       | 22.6       |
| 53°31'     | 54°52'     | 37.2       | 31.1       | 27.7       |
| 52°09'     | 53°31'     | -39.7      | 6.9        | 26.9       |
| 50°48'     | 52°09'     | -32.8      | 27.6       | 23.6       |
| 49°27'     | 50°48'     | -12.0      | 35.7       | -12        |
envelope (CE), in addition to the action of the stellar wind, producing the axisymmetric morphology (e.g. Bond & Livio 1990; Exeter, Pollacco & Bell 2003). The CE phase would reduce the separation of the pair, for angular momentum of the CE is gained at the expense of the orbital energy of the secondary. This process may also lead to a spin-up of the core which would further aid in producing an axisymmetric nebular shape.

Incidentally, the bipolar model presented here (Fig. 7) is of course not a unique solution to the actual morphology and kinematics of LoTr 5; there are a wide range of more complicated structures and outflows that could be devised to produce, using the XSHAPE code, some of the major features seen in the image and observed pv arrays. However, the strength of the present prediction is that a very simple, and plausible, bipolar structure generates the major features within the images and pv arrays.

3.3 Possible interactions with the ISM

The causes of any interaction with its local ISM are the expansive motions of LoTr 5 of ≈27 km s\(^{-1}\), combined with its large bulk motion of ≥60 km s\(^{-1}\) (for a distance of ≥500 pc) as indicated by the westerly PM of the central star IN Com (Section 1) and the modest radial velocity of the star (Section 3.1).

First, only the effects of expansive motions are considered. Given the high Galactic latitude of LoTr 5 along with the Hipparcos distance lower limit (Section 1), it is interesting to consider quantitatively whether or not such an expansive interaction with the surrounding ISM is dynamically significant for LoTr 5; at a distance of ≥500 pc from the Galactic plane, LoTr 5 is likely to be expanding into \(n_e \geq 1.27 \times 10^{-2} \text{ cm}^{-3}\) material (Gómez, Benjamin & Cox 2001). Using the angular size of LoTr 5 to estimate its volume, a swept-up mass of ISM material of ≥0.0032 \(M_\odot\) would be expected, assuming a hydrogen ionization fraction of 0.09 (Bruhweiler & Cheng 1988). This is significantly less than the 0.2 \(M_\odot\) typically ejected by PN progenitors (Kwok 1994). Therefore the local ISM would not be expected to affect the dynamical evolution of LoTr 5 at this distance from the Galactic plane if only expansive motions are considered.

Could the large motion through the ambient ISM be causing significant interaction? The central stellar system IN Com has a large PM (see Section 1). This is directed away from the curious ‘hole’ noticed in the imagery (Figs 1 and 2), and it was thought possible (Graham, Meaburn & López 2003) that this could have been the location of the star at the start of the PN outflow. However, a distance of ≥500 pc implies a dynamical age of ≥2.0 \(\times 10^4\) yr as given by the nebular diameter combined with its expansion velocity. At its current PM, IN Com will move approximately four times the angular separation between the ‘hole’ and the present position of IN Com in a dynamical time of 2.0 \(\times 10^4\) yr. Therefore IN Com is unlikely to have been located at the position of the hole when nebular expansion began.

Figure 6. XSHAPE model image of LoTr 5 and pv arrays for (a) path 2, (b) path 3, (c) path 4, (d) path 5 and (e) path 1 in Fig. 2. The positions of the paths are shown on the model image as dashed lines. The boxes surrounding the model pv arrays delineate the extent of the pv array data in Figs 3 and 4.
is certainly on the expected side of the nebula as the PM of IN Com is almost due west. However, there is no apparent drop in ionization level in this region, as it is bright in [O III] 5007 Å along with the rest of LoTr 5.

One observational consequence of a 90 km s$^{-1}$ interaction with the ISM would be the generation of soft X-ray emission for a post-shock temperature of $\sim 10^5$ K. If such emission is found to be coincidental with the western arc in Fig. 1 then such an interaction would be confirmed. None is evident in the ROSAT images of Kreysing et al. (1992).

4 CONCLUSIONS

The morphology of LoTr 5 is now shown to be considerably asymmetric. In particular, a western arc of emission has been discovered. This complexity is confirmed by the parallel discovery of [O III] 5007-Å line profiles with up to three velocity components.

This morphology and kinematics are partially modelled by a bipolar structure viewed nearly end-on, i.e. with the bipolar axis tilted by 17° to the sight-line. Within this model, each lobe is expanding at $\approx 27$ km s$^{-1}$.

This tilt of the bipolar axis is nearly perpendicular to the plane of the central binary system of IN Com. This is consistent with a dynamical model for the creation of bipolar nebulae by binary systems.

The enhanced [O III] 5007-Å emission along the newly discovered western arc could be a consequence of a significant interaction with the local ISM as a result of the expansive motions of the bipolar lobes and $\geq 60$ km s$^{-1}$ bulk motion of the whole nebula. A soft X-ray source coincident with this arc would confirm this interaction.

ACKNOWLEDGMENTS

JM thanks the Royal Society for support in 2003 May for his visit to UNAM (Ensenada) when the first draft of this paper was written. MFG and DJH thank PPARC for their Research Studentship and Associateship respectively. We acknowledge the excellent support of the staff at the SPM observatory during these observations. JAL gratefully acknowledges financial support from CONACYT (Méx) grants 32214-E and 37214 and DGAPA-UNAM IN114199.

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