The shape of the LoTr 5 planetary nebula

Noah Brosch* and Yehuda Hoffman†

1 Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA
2 Kapteyn Astronomical Institute, University of Groningen, PO Box 800, 9700 AV Groningen, the Netherlands

Accepted 1998 September 24. Received 1998 September 21; in original form 1998 January 19

Abstract

We observed the large and faint planetary nebula around IN Com in Hα and N II light with a coronagraphic charge-coupled device on the Wise Observatory reflector, blocking the light from the central star. Our goal was to provide a second image of the object with which to confirm the features seen in the only published photograph from the paper by Longmore & Tritton reporting the discovery of this object. The nebula is extremely faint, but a combination of images totalling about one and a half hours of exposure shows it fairly well. A novel image processing algorithm has been applied to the noisy image in order to reveal faint extended details of the images. The algorithm is based on a non-linear self-adaptive filter applied to the wavelet transform of the image. The nebula is not round or elliptical, but shows a two-lobed or possibly three-lobed morphology, as well as a peculiar hole-like feature east of the central star. There is definite east--west and slightly less definite north--south asymmetry.

Key words: binaries: close -- circumstellar matter -- stars: imaging -- stars: individual: IN Com -- planetary nebulae: individual: LoTr 5.

1 Introduction

The planetary nebula (PN) LoTr 5 = 339.9 ± 88.4, around the star IN Com, was discovered by Longmore & Tritton (1980, hereafter LT80). It has the distinction of being the highest galactic latitude PN at b = 88° and is very faint. Although many publications analysed the central star, the only image of the PN appears in the discovery paper and is from a IIIaJ+GG395 plate from the UK Schmidt ESO/SRC Southern Sky Survey; the PN is not visible on the Palomar Sky Survey. The image shown by LT80 shows some deviations from roundness as well as some regions within the PN envelope with fainter surface brightness. Bond & Livio (1990) count LoTr 5 among the elliptical morphology PNs and explain this as the influence of an extreme to moderate density contrast produced by binary ejection, followed by shaping by a fast wind. Tweedy & Kwitter (1996) classify it as a point-symmetric PN and conclude that it shows no interaction with the interstellar medium (ISM).

LoTr 5 is peculiar because its central star is a possible triple system. We were drawn to it following a study of ultraviolet (UV) sources in the direction of Coma, observed by the FAUST telescope (Brosch et al. 1998), where IN Com was detected as a 1650-Å UV source. A literature search revealed that the star is classified optically as G5III, but International Ultra-violet Explorer (IUE) spectra show an upward turn for λ ≤ 2300 Å in the spectral energy distribution, to the shortest UV wavelengths observed (Feibelman & Kaler 1983), an indication of a very hot body in the system. Various photometric and spectroscopic periods have been reported for IN Com, ranging from 1.2 to 5.9 and even 2000 d (Schnell & Purgathofer 1983; Malasan, Yamasaki & Kondo 1991; Jasiewicz, Duquennoy & Acker 1987; Jasiewicz et al. 1994; Strassmeier et al. 1997a; Strassmeier, Hubl & Rice 1997b).

IN Com is an X-ray source (Apparao, Berthiaume & Nousek 1992; Kreyzing et al. 1992). The emission is soft and corresponds to a body at 1–2×10^7 K. The system is also an Extreme Ultraviolet Explorer (EUV) source in the 58–174 Å band (Fruscione et al. 1995). This is presumably one of the hottest known stars (T_{\text{eff}} ≳ 120000 K; Feibelman & Kaler 1983), but may not be the only X-ray source in the system.

The distance estimates to LoTr 5 range from 80 pc (Buonatiro 1993) to 6.3 kpc (recalculated by Jasiewicz et al. 1996). The Hipparcos Catalog lists for IN Com a trigonometric parallax consistent with zero (0.83 ± 1.17 mas yr^{-1}), locating the object at a distance larger than ~0.2 kpc (3σ). A 100-pc distance to IN Com would translate its Hipparcos-measured proper motion into a transversal velocity of the same magnitude as its radial velocity (–9 km s^{-1} in Jasiewicz et al. 1994; –9.6 ± 0.4 km s^{-1} in Strassmeier et al. 1997a).

IN Com has been reported to be a triple star (Malasan et al. 1991), consisting of an sdO star (M_{*} ≈ 1.1 M_{\odot}) orbiting, with a ~2000-d period, a close binary system made of a G5III star and a low-mass star. Jasiewicz et al. (1996) argued that the close binary consists of the 1.1-M_{\odot} G5III star and the sdO star (M_{*} ≈ 0.6 M_{\odot}, typical of a
2 OBSERVATIONS

We observed IN Com with the Wise Observatory (WiseObs) 40-inch (~1-m) reflector in order to obtain a new image of the nebula. Preliminary attempts to image the nebula directly with a 50-Å full width at half-maximum (FWHM) Hα filter whose transmission profile is centred on 6562 Å were unsuccessful. We attribute this to light scattered within the telescope from the G5 central star, as argued by Malasan et al. (1991), its evolution should have happened almost in isolation and one may expect the PN to be symmetrical. If, on the other hand, the interpretation by Jasniiewicz et al. (1996) is correct, one should expect the PN to show some asymmetry. A detailed morphological study of the nebula requires first a confirmation of the general features seen in the broad-band image published by LT80, and, even better, an image obtained in an emission line to disentangle continuum emission from the nebula proper. We present here a new image of LoTr 5 obtained in Hα, which contains morphological evidence to support the second possibility, namely of the PNN being one component of a close binary.

3 RESULTS

The image in Fig. 1 shows a roundish nebulosity around the central star of LoTr 5 (IN Com), and is very similar to that reproduced in LT80. The central star of the PN is mostly occulted by the finger, along with the other bright star (11.3 mag) in the field, south of IN Com and close to the edge of the imaged field. Note the non-uniform distribution of nebular intensities. The nebulosity is much more extended west of the occulting finger than east of it. A similar asymmetric distribution of intensities is apparent in the north–south direction, where the nebulosity is more extended in the east–west direction, north of IN Com. The subjective asymmetry is confirmed also by comparing ‘typical’ cuts through the nebula; one in the east–west direction across the northern part of the nebula is brighter by a few per cent than one to the south of IN Com.

In general, if one could reduce the nebulosity to its two principal components, it could be described as two ‘blobs’. One lobe of the
PN is large and extends west of IN Com, north and south of the star. The other lobe is much smaller and is located north-east of IN Com. There is substructure within the two blobs, but our images do not reveal this clearly. If anything, it is possible that the large blob to the west is composed of two smaller blobs. The structure of the nebula is probably two-lobed, or possibly three-lobed. The same structure, by the way, is evident in the original image of LT80 but has not been remarked on. The size of the nebulosity, as measured from our combined image, is $\sim 490 \times 530$ arcsec$^2$. This is slightly smaller but rounder than given by LT80 ($490 \times 560$ arcsec$^2$). Note that it is difficult to mark exactly where the nebulosity ends and it is possible that we are missing the outer regions of the PN, which are probably exceedingly faint.

In order to verify the reality of the asymmetric nebulosity we used a wavelet transform technique with filtering in wavelet space, to emphasize the large-scale features. Our image processing approach is to trim all the data to lie in between the 20 to 30 DNs, the range of the features seen when displaying different DN levels. To suppress the shot noise of the image, a non-linear self-adaptive filter has been applied to the digital wavelet transform (DWT) of the image using the Daubechies-12 wavelet representation (Press et al. 1992). The denoising algorithm is fully effective.

Figure 2. H$\alpha$ image of IN Com and LoTr 5: original (top left) and after wavelet cleaning (top right). The image parameters are as for Fig. 1. The other panels show (lower left) the wavelet spectrum (solid line) and its truncation with extension (dotted line), and (lower right) two cuts through the centre of the image (north-south = upper and east-west = lower), with the original data as the dotted line and the denoised one as the solid line. The cuts have been shifted vertically by 10 data numbers (DNs) to separate them clearly on the plot.
described in Hoffman (1998) and its various steps are illustrated in Fig. 2. This algorithm has recently been applied to the analysis of the Sunyaev–Zeldovich effect and of the X-ray surface brightness of rich clusters of galaxies (Zaroubi et al. 1998).

The raw image is shown in the upper left panel of Fig. 2. The DWT is applied to the data and the absolute values of the wavelet coefficients are sorted in decreasing order. The sorted wavelet spectrum of the raw image is shown as the solid line in the log–log plot shown in the lower left panel of Fig. 2. Note the appearance of two approximate power laws, one for the \( \sim 0.05 \) per cent highest-amplitude coefficients, and a much shallower one for the rest of the coefficients. This is typical behaviour found in many astronomical and other kinds of images. Noisy images, characterized by distinct non-random features, show a dual power law of the sorted wavelet spectrum. Clean, noiseless images of this kind exhibit a single approximate power-law behaviour of their sorted wavelet spectrum. The assumption made here, which is confirmed by the analysis of simulated images (Hoffman 1998), is that the high end, with the steep power law, corresponds to the clean input signal, while the low end, with its shallower power law, is dominated by the noise.

An adaptive non-linear filter is applied to the wavelet coefficients such that the low-amplitude coefficients are suppressed, in order to recover the single power-law behaviour (Hoffman 1998). This filter is non-linear, because it depends only on the amplitude of the coefficients and not on scale or position. It is self-adaptive, because it extrapolates the spectral high-end behaviour to the entire wavelet space, from approximately the point \( 5 \times 10^{-4}, 20 \) in the lower left panel of Fig. 2. The horizontal line in the lower left panel of Fig. 2 shows the threshold value that distinguishes the signal-dominated from the noise-dominated regimes. The dotted line shows the sorted and filtered wavelet spectrum. One should note the fundamental difference between the non-linear filter used here and the commonly used linear filters. The latter operate by smoothing, namely suppressing, some of the Fourier (for example) modes according to their location in reciprocal space, thus leading to an inherent loss of resolution. Non-linear filters, such as the one used here, suppress only the low-amplitude coefficients regardless of their scale and position, thus avoiding a loss of resolution.

Fig. 2 shows the denoised image in the top right panel. A more quantitative presentation of the original and denoised images is given by the lower right panel, which shows horizontal and vertical line cuts passing near the centre of the denoised image. Two plots are presented, originating from the noisy (dotted line) and denoised (solid line) image. One plot (corresponding to the horizontal cut) is arbitrarily shifted in amplitude by 10 DN relative to the other for the sake of clarity, and shows the amount of noise suppression achieved by the denoising algorithm. The Hα image shows, after denoising, the basic structural features of the PN that were visible in our original image and in that of LT80. The details are clearer in the denoised image, and the asymmetric light distribution is easily perceived. Note that while the pattern of ‘spillover’ light originating from the two stars hidden behind the occulting finger is very similar, there are two brighter intensity peaks in the western part of the PN, while in the eastern part only a faint minor peak is seen. A more quantitative analysis would be beyond the scope of this paper.

Note in the top right panel of Fig. 2 that the low-intensity patch east of IN Com is still present, although its shape has been somewhat modified by the properties of the transform. Some artefacts have been introduced, such as the two streaks parallel to the occulting finger and its extension to the north, but in general the image is easier to evaluate morphologically than the original one. Both the east–west and north–south asymmetries have been retained in the wavelet-cleaned image; this indicates that they are intrinsic to the nebulosity.

4 DISCUSSION

It is now possible to evaluate the PN morphology. Adopting the criteria set by Stanghellini, Corradi & Schwarz (1993), we note that the images show (a) two main axes, one approximately north–south and the other approximately east–west, and (b) a waist-like region near IN Com, oriented generally in the east–west direction. Based on these, and considering the additional structure in the outer regions of the PN, one could classify LoTr 5 as a ‘bipolar’ PN, perhaps belonging to the subclass BM. In any case, the PN does not appear to be symmetric.

Asymmetry in a PN can be caused by an interaction between the nebular gas and the ISM (Dgani & Soker 1997). The Atlas of Galactic Neutral Hydrogen (Hartmann & Burton 1997) was consulted to establish whether the ISM in the immediate vicinity of LoTr 5 shows signs of disturbance. The only significant H I signal near IN Com appears at \( v_{\text{LSR}} = 0 \text{ km s}^{-1} \) (LSR = local standard of rest) and the distribution of neutral hydrogen does not appear to be disturbed. For this reason, we believe that interaction with the ISM is not the shaping factor of this PN. This was also the conclusion of Tweedy & Kwitter (1996) based on the LT80 image.

The morphology described above shows a peculiar ‘hole’ east of IN Com, which is visible in the LT80 photograph, in our original combined image and in the wavelet reconstruction (though its shape changed slightly). In principle, a round feature could be a shadow cast on to the nebulosity by a foreground extended and opaque object, such as a dark globule. We consider this an unlikely possibility, because both the IRAS Point Source Catalog and the Faint Source Catalog do not list a 100-μm source at the high galactic latitude location of IN Com, and we believe this asymmetry to be intrinsic to the PN. Soker (1997) reviewed different mechanisms that may shape PNe. A patch of low surface brightness could be the result of a star within the nebula blowing a clear(er) patch through the PN material. This is also not a viable option for LoTr 5, as our images do not show a star within the ‘hole’. We also note that Soker classified LoTr 5 as belonging to the common envelope family; these objects are expected to form elliptical PNe, if the primary survives to the AGB stage, and the hole-like feature could not be explained in this case.

There are indications that the hot component of IN Com has a strong and fast stellar wind observed in high-excitation UV lines (Modigliani, Patriarchi & Perinotto 1993; Feibelman 1994). The fast wind and the presence of high-excitation spectral lines indicate that this star is a few 10^5 yr past its AGB. It may be possible that the stellar wind played some role in the shaping of this PN, although how it could have ‘carved out’ the cavity is not clear.

One of the latest analyses of the system (Jasniewicz et al. 1996) puts at the centre of the PN a close binary consisting of a hot sdO star and a G5III star, where the latter star spins close to breakup velocity with \( P_0 = 5.9 \text{ d} \) and produces the photometric light curve by its spotted surface. This raises another possibility of explaining the shape on the PN through magnetic confinement of the stellar wind, which could be eased in the case of a binary where the envelope was spun-up (cf. Livio 1997). The present-day sdO star could have been spun-up by tidal interaction with its companion in an earlier evolutionary phase, just as the companion seems to be spun-up today. However, this possibility produces as a first
approximation axisymmetrical configurations (Livio 1997), not localized rarefactions in the PN as observed in this case.

5 CONCLUSIONS
A new image of the planetary nebula LoTr 5 (IN Com) was obtained in Hα and N[II] light as a combination of CCD images taken with a coronagraph on the Wise Observatory telescope. The images show an asymmetric nebula, arguing for the presence of a close binary nucleus in this PN, with one component being the hot star that ejected the nebula. Observations with EUVE will possibly establish the temperature of the hot star and, through a comparison with models, its age on the cooling tracks. The mechanism that shaped this PN, and in particular created a hole-like feature east of the central star, has not been identified.

ACKNOWLEDGMENTS
UV research at Tel Aviv University is supported by grants from the Ministry of Science and Arts through the Israel Space Agency, from the Austrian Friends of Tel Aviv University, and from a Center of Excellence Award from the Israel Science Foundation. NB acknowledges support from a US–Israel Binational Award to study UV sources measured by the FAUST experiment, and the hospitality of STScI during his sabbatical. YH acknowledges support from the S. A. Schonbrunn Research Endowment Fund, and the Israel Science Foundation (103/98). We acknowledge the use of the CDS database at Strasbourg, in particular the on-line access to the Hipparcos and Tycho catalogues. We are grateful to Mario Livio and Noam Soker for reading and commenting on an early draft of this paper. Steve Larson is acknowledged for providing the original coronagraph, used for the observations presented here.

REFERENCES
Apparao K. M. V., Berthiaume G. D., Nousek J. A. 1992, ApJ, 397, 534
Bond H. E., Livio M. 1990, ApJ, 355, 568

This paper has been typeset from a TeX/LaTeX file prepared by the author.