

The Mid-IR Emission Structure of IRAS 16594-4656

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Abstract. We report TIMMI2 diffraction-limited mid-IR images of the multipolar PPN IRAS 16594-4656. By using the Lucy-Richardson deconvolution algorithm we recover a two-peaked morphology in the innermost region at 8.6 μm and 11.5 μm . We interpret the observed mid-IR structure as the detection of the two limb-brightened peaks indicating the presence of a dusty toroidal structure in IRAS 16594-4656. We find that the supposed biconical openings of the dust torus are in good agreement with one of the bipolar outflows identified in the HST optical images.

1. IRAS 16594-4656

IRAS 16594-4656 (GLMP 507; hereafter I16594) was identified as a proto-planetary nebula (PPN) candidate on the basis of its IRAS colours by Volk & Kwok (1989). It shows a double-peaked spectral energy distribution which is dominated by a strong mid- to far- infrared peak caused by dust emission that is much brighter than the peak in the near-infrared. The HST optical images show the presence of a bright central star surrounded by a multiple-axis bipolar nebulosity (dominated by scattered light) with a complex morphology at some intermediate viewing angle (Hrivnak, Kwok & Su 1999).

There are several proofs of the presence of a circumstellar disc or torus (as an equatorial density enhancement) in I16594. The highly collimated structure seen in the HST optical images and the non-detected radio-continuum emission by van de Steene & Pottasch (1993) indicate that the emission lines observed in the optical spectrum are the result of the shock excitation produced by a fast

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bipolar wind from the central source. In agreement with this hypothesis García-Hernández et al. (2002) detected H_2 shock-excited emission in the direction of I16594. In addition, Su et al. (2003) observed 10% polarization around the central source, suggesting the presence of a circumstellar torus.

All previous studies of I16594 confirm the basic model of PPNe where an enhancement of the equatorial density (torus) could obscure the central star in visible light and is collimating the fast wind proceeding from the central star. This model can be tested by obtaining high-resolution mid-IR images of I16594. van de Steene, van Hoof, & Wood (2000) did not detect extended emission in their N-band images of I16594, but they observed with a pixel scale of $0.66''$, the weather conditions were very poor and they did not correct for the PSF effects.

2. Mid-IR observations and data reduction

The observations were carried out in 2001 October 9 with the TIMMI2 mid-IR camera coupled to ESO 3.6m telescope (La Silla). TIMMI2 has an array of 320×240 pixels with a pixel scale of $0.2'' \times 0.2''$. The observational conditions were very good and we obtained the mid-IR images (at $8.6 \mu\text{m}$ [N1] and $11.5 \mu\text{m}$ [N11.9]) at the diffraction limit of the telescope. We used the standard nodding/chopping mid-IR observational technique and the basic data reduction process to obtain a final image per filter. The flux calibration was made using the averaged conversion factors derived from the observations of a number of standard stars at different air masses. We removed the effects of the PSF by using the Lucy-Richardson deconvolution algorithm implemented in IRAF in order to recover the emission structure for each filter. In Figure 1 we display the original/raw images with the corresponding deconvolved ones for every filter.

3. Raw and deconvolved mid-IR morphology of the nebula

We can identify two main mid-IR emission regions in I16594 in the two filters (see Figure 1, left). An extended halo which is approximately elliptical ($\leq 40\%$ of the peak intensity) and an elongated emission core ($> 40\%$ of the peak intensity). We fitted the emission halo with elliptical isophotes in order to determine the source centre. This was determined by averaging the central coordinates of the isophotes with 20–40% of the peak intensity to avoid any contamination from the core structure. The images displayed in Figure 1 have been centred on this position. Because the central star has a B7 spectral type (van de Steene, Wood, & van Hoof 2000), no contribution in $10 \mu\text{m}$ to the flux observed is expected. In addition, Hrivnak, Kwok, & Su (1999) found that the contribution of the photospheric component to the total flux in the mid-IR is only $\sim 3\%$. For this reason, we have considered the photospheric contribution negligible.

The deconvolved N1 and N11.9 images are shown in Figure 1 on the right. We recover a two-peaked morphology in the innermost region in the two filters. The two detected peaks are approximately orientated along the north-south direction (P.A. $\sim -10-170^\circ$) and we can define a symmetry axis in the east-western direction (P.A. $\sim 80-260^\circ$). We interpret the mid-IR morphology seen in the deconvolved images as the evidence of the two limb-brightened peaks corresponding to a dusty toroidal structure in I16594. We are sure that the

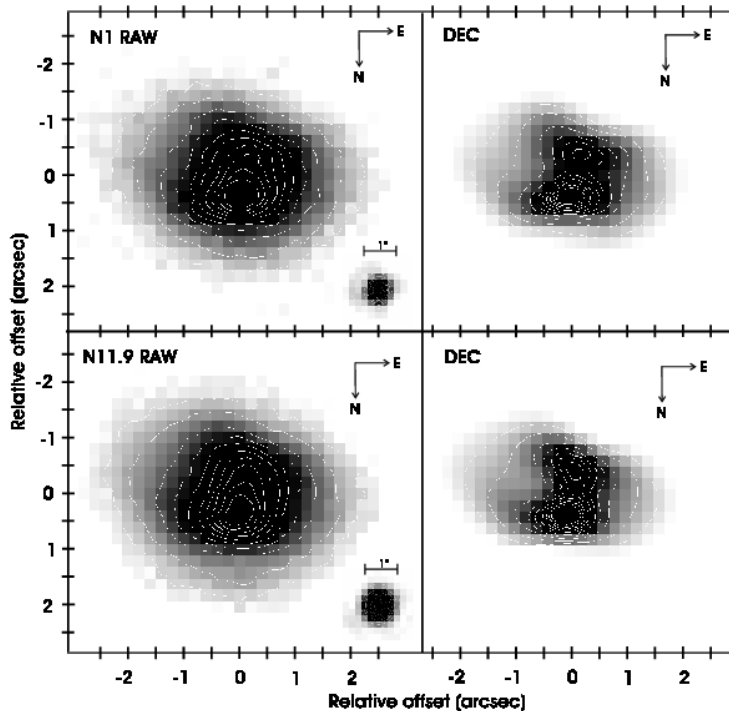


Figure 1. Raw mid-IR images of I16594 in N1 ($8.6 \mu\text{m}$) and N11.9 ($11.5 \mu\text{m}$) filters (left, from top to bottom) and the corresponding deconvolved images (right). The thick marks show relative offsets from the centre of the nebula in arc seconds. Contours range from 10% to 90% of the peak intensity (in steps of 10%) and we have added the outermost contours, which correspond to 5% of the peak intensity. The insets show the standard star PSFs in each filter.

I16594 deconvolved structure is real for two reasons: first because we have a large signal-to-noise ratio in the raw images and second we obtain a similar emission structure in N1 and N11.9. Otherwise, we find that the north-peak (P.A. $\sim -10^\circ$) is brighter and more extended than the other. Ueta et al. (2001) found a similar asymmetric appearance in IRAS 22272+5435.

4. Evidence for precession in IRAS 16594-4656

We infer pairs of elongated structures with at least four different bipolar axis at P.A. $\sim 34^\circ$, $\sim 54^\circ$, $\sim 84^\circ$ and $\sim 124^\circ$ from the HST optical images. The presence of different bipolar axis suggests that material has been ejected episodically from a precessing/rotating source. Similar structures are also detected in more evolved PNe (e.g. Guerrero & Manchado 1998). We have displayed the I16594 optical HST image (taken from the HST Data Archive) overlaid with the contours of the deconvolved mid-IR images in Figure 2. We find that the mid-IR emission symmetry axis approximately coincides with the bipolar axis located at P.A. $\sim 84^\circ$.

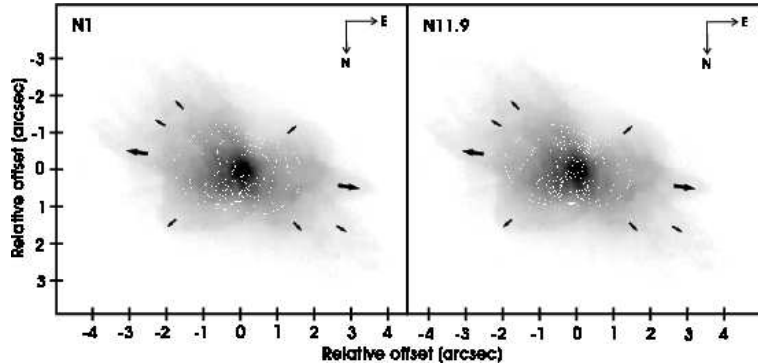


Figure 2. Optical HST image of I16594 (taken from the HST Data Archive) overlaid with contours of the deconvolved mid-IR images in the N1 ($8.6 \mu\text{m}$) and N11.9 ($11.5 \mu\text{m}$) filters. The displaying conventions follow those of Fig.1. The big arrows indicate the directions of the optical prominences that coincide with the supposed biconical openings of the dust torus. The other bipolar axis directions identified in I16594 have been marked with small arrows.

The optical prominences towards the west (P.A. $\sim 260^\circ$) and east (P.A. $\sim 80^\circ$) are in good agreement with the supposed biconical openings of the dust torus. This finding may thus indicate that the ejected material proceeding from the central source is at present collimated by the dust torus along the east-west direction (P.A. $\sim 80-260^\circ$). The other bipolar outflows may be the result of episodic mass loss processes and could be the signature of a precessing system.

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