On the properties and evolution of proto-planetary nebulae

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Chapter 4

IRAS 17150–3224: a young, optically bipolar, proto-planetary nebula

Abstract

We have carried out optical, near-infrared and CO and OH observations of the cool infrared source IRAS 17150–3224. We argue that the source is a young proto-planetary nebula. Its spectral type is G2I. From radiative transfer modelling we find that the AGB wind terminated less than \( \sim 150 \) yr ago. We derive a mass loss rate on the AGB of \( \dot{M} \sim 4 \times 10^{-5} M_\odot \text{yr}^{-1} \). The optical image shows a bipolar reflection nebula. The optical observations indicate the presence of a dust torus which inhibits a direct view of the central star, but allows illumination of the reflection lobes. The OH maser spectra suggest that at large distances from the star the circumstellar shell is more or less spherical, which indicates that a transition from spherically symmetric to equatorial outflow took place less than \( \sim 10^3 \) yr ago. The OH spectra also suggest an appreciable acceleration of the stellar wind over the masing regions. A large degree of circular polarization is present in the OH 1665 MHz maser. A field strength of the order of 0.2 kG on the stellar surface is required to account for the polarization. It is argued that upon the transition from AGB to post-AGB the magnetic field may have become capable of dominating the gas motions.

4.1 Introduction

The idea that AGB stars are the progenitors of planetary nebulae, originally suggested by Shklovskii (1956), is now widely accepted (see Habing 1990, for a review). The objects in transition between these two evolutionary stages, the proto-planetary nebulae (PPNe), undergo a dramatic change during only about a few thousand years. This phase in stellar evolution is still poorly understood. A systematical search for these objects has only become possible after the IRAS infrared sky-survey.

One of the problems in PPN evolution theory concerns the morphology of the circumstellar envelope. A large fraction of the planetary nebulae show an asymmetrical shape in the visible (Balick 1987). On the contrary nearly all OH/IR stars have a more or less spherically symmetric dust/gas envelope, with a few notable exceptions which may already be in the transition phase (Chapman 1988 and references therein). It is not known why and when during the transition phase this change in envelope structure occurs. It is commonly assumed that the actual shaping of the planetary nebula takes place when a fast wind from the hot central star of the young PN ploughs through
the remnant AGB shell (e.g. Kwok et al. 1978). The three best-studied bipolar PPNe all show signatures of high-velocity outflow. These are CRL618 (Carsenty and Solf 1982), Roberts 22 (Allen et al. 1980), and CRL2688 (Nguyen-Q-Rieu and Bieging 1990). On the basis of hydrodynamical modelling Icke et al. (1989) have argued that an initial density contrast must already be present in the AGB-star phase. In this paper we will address the question of the origin of the asphericity for one particular object, IRAS 17150–3224. We show that this object is a bipolar PPN, in an earlier evolutionary phase than the three aforementioned objects.

IRAS 17150–3224 (= RAFGL6815S) is one of 62 PPN candidates in an infrared complete sample which we selected from the IRAS Point Source Catalogue, mainly on the basis of their IRAS colours (Hu et al. 1990, 1992, Chapter 2). We identified all candidates on POSS or ESO/SERC plates. One of the optically extended objects in this sample, IRAS 17150–3224, showed a strikingly asymmetrical shape, which warranted further study.

IRAS 17150–3224 has previously been observed in the CO (J=1−0) line (Zuckerman and Dyck, 1986) and in the OH 1612 MHz maser line (te Lintel Hekkert, private communication 1988, te Lintel Hekkert et al. 1991). van der Veen et al. (1989) obtained near-infrared photometry of this source. On the basis of its spectral energy distribution they considered the object to be a PPN candidate.

We have made extensive observations of this object during the last three years. In Sect. 4.2 we present the results of optical spectroscopy, optical and K-band direct imaging, optical and near-infrared photometry, (sub-)mm wave continuum measurements, and OH maser (1612, 1665/67 MHz) and CO (J=2−1, J=1−0) observations. In Sect. 4.3.1 we provide evidence that the object is a PPN. Subsequently the properties of its dust-gas envelope are discussed. We find evidence for a strong stellar magnetic field, which may have played a role in the shaping of the nebula.

4.2 Observations

An accurate position of IRAS 17150–3224 was obtained from N-band photometry using the 1m telescope equipped with the bolometer at ESO, La Silla, in April 1990. The position of the near-infrared counterpart was determined by K-band photometry using the same telescope equipped with the InSb detector. The positions were measured by scanning the source through a 15" diaphragm. The optical position was measured on prints of the ESO/SERC plates, and refers to the position at peak intensity.

The results of the position determinations are listed in Table 4.1, in which the IRAS position is also given. The positions of the source in the different wavelength bands coincide well. The N-band magnitude is 1.79 which corresponds to a flux at 10 μm of 2.4 × 10^{-13} Wm^{-2}μm^{-1}. This value is similar to the one derived from the IRAS LRS spectrum (IRAS Science Team, 1986). A finding chart of IRAS 17150–3224 is presented in Fig. 4.1
4.2. Observations

Table 4.1: Optical and infrared positions of IRAS 17150–3224

<table>
<thead>
<tr>
<th>band</th>
<th>$\alpha$ (1950.0)</th>
<th>$\delta$ (1950.0)</th>
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<tbody>
<tr>
<td></td>
<td>(h)</td>
<td>(m)</td>
</tr>
<tr>
<td>IRAS</td>
<td>17</td>
<td>15</td>
</tr>
<tr>
<td>N-band</td>
<td>17</td>
<td>15</td>
</tr>
<tr>
<td>K-band</td>
<td>17</td>
<td>15</td>
</tr>
<tr>
<td>optical</td>
<td>17</td>
<td>15</td>
</tr>
</tbody>
</table>

4.2.1 Wide-band photometry and CCD direct imaging observations

Near-infrared photometry was obtained in March 1989, using the 1m ESO telescope equipped with the InSb detector and a 15" diaphragm, employing standard stars of Koornneef (1983). The same telescope, equipped with the bolometer and a 15" diaphragm, was used to obtain N-band photometry.

In May 1988 sub-mm photometry at 0.8 and 1.1 mm was obtained, using the JCMT equipped with the UKT14 bolometer at Mauna Kea, Hawaii. Uranus (3'78 diameter, 48.09 Jy at 1.1 mm, 92.32 Jy at 0.8 mm) and Mars (8'10 diameter, 510.54 Jy at 1.1 mm, 1120.59 Jy at 0.8 mm) were used for flux calibration. The telescope’s half-power beam width (HPBW) was 19" at 1.1 mm. A chop throw of 150" in the East-West direction was used. Measurements at 1.1 mm with an offset of 10" North, East, West and South of the central source position did not yield any significant signal ($S_\nu < 0.05$ Jy).

As IRAS 17150–3224 shows an extended image on the POSS and ESO/SERC plates, we used direct CCD imaging to obtain $BVRI$ photometry. The CCD direct imaging observations were made in March 1989, using the 1.5m Danish telescope at ESO. The Johnson-Cousins $BVRI$ photometric system was used, employing the standard stars in the E-regions.

The results of the optical, near-infrared and (sub)mm photometry are listed in Table 4.2, together with the IRAS data. The $B$, $R$, and $I$ CCD images are shown in Fig. 4.2

The optical counterpart of IRAS 17150–3224 is extended over ~ 10" x 6". The $B$-image shows a double-lobed structure. Towards longer wavelengths, the gap between the lobes is progressively filled-in. The bright core in the north-western lobe is slightly elongated. In all wavelength-bands its full width at half maximum (FWHM) is 2'3 along the object’s major axis, and 1'7 along the minor axis (pixel size 0'5, FWHM of the stellar images 1'4).

We were able to obtain a $K$-band image, using IRAC on the ESO 2.2m telescope. The $K$-band image (pixel size 0'9) shows no extension of the near-infrared source. Because of the lack of reference stars in the $K$-band image, it is not possible to directly compare the position of the $K$-band source with the position of the optical image. As the separation between the cores of the two lobes is only 3.5 arcseconds, the position obtained from the near-infrared photometric observations is not accurate enough to determine whether the near-infrared source is situated between the two lobes, or...
Figure 4.1: Identification of the optical counterpart of IRAS 17150-3224 within the IRAS position error box (ESO/SERC R plate). North is up, East is to the left.

Figure 4.2: CCD images of IRAS 17150-3224. From left to right B-band, R-band, and J-band image. The image scale is 0.5 arcsec/pixel.

Table 4.2: Photometric data of IRAS 17150-3224

<p>| | | | | | | | |</p>
<table>
<thead>
<tr>
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<td>$I$</td>
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<td>0.22±0.05</td>
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</table>
4.2. Observations

4.2.2 Optical spectroscopy

Optical spectra were taken in March 1989 using the ESO 1.5 m telescope equipped with a B&C spectrograph. The detector was a high resolution RCA CCD. The spectrum covers the range from 4000 to 6800 Å and has a dispersion of 2.75 Å/pixel. The slit was centered on the object’s bright core and crossed the nebulosity in the right ascension direction. Figure 4.3 shows a normalized spectrum of the core of IRAS 17150–3224.

We use the ratio FeI λ4920/H\(\beta\) and the strength of the G-band as classification criteria for the spectral type. The MgI ‘b’ and NaI D lines are used as luminosity criteria. The weakness of MgI ‘b’ compared to H\(\beta\) and the great strength of the NaI D lines indicate a high luminosity. From comparison with the spectra in the ‘Library of Stellar Spectra’ (Jacoby et al. 1984) we derive for IRAS 17150–3224 a spectral type G2I.

4.2.3 Radio line observations

OH observations were carried out in June 1990, and in April 1991 with the radio telescope at Nançay, France. The half-power beamwidth (HPBW) was 3′5 in right ascension and 18′ in declination. The flux to antenna temperature ratio was 1.1 Jy/K. The system temperature was ~ 60 K. The backend consisted of a 1024 channel autocorrelator which was split into four bands of 256 channels each. The OH 1612 MHz satellite line was observed simultaneously with either the main line at 1665 MHz or with the main line at 1667 MHz. The lines were simultaneously observed in both left- and right hand circular polarization. Baseline subtraction was performed by frequency switching. The velocity coverage and the velocity resolution were 73 km s\(^{-1}\) and 0.29 km s\(^{-1}\), respectively, during the 1990 observations. During the 1991 observations the velocity resolution was 0.018 km s\(^{-1}\) for the OH 1612 MHz line, 0.14 km s\(^{-1}\) for the 1667 MHz line and 0.07 km s\(^{-1}\) for the 1665 MHz line. The OH maser line profiles obtained in 1991 are presented in Fig. 4.4.
Figure 4.4: OH observations. a, b OH 1612 MHz LCP, RCP respectively, c, d OH 1667 MHz LCP and RCP, e, f OH 1665 MHz LCP and RCP

Figure 4.5: CO (J=2–1) spectrum
4.2. Observations

Table 4.3: OH and CO line parameters

<table>
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<th>transition</th>
<th>$&lt;V_{\text{LSR}}&gt;$</th>
<th>$\frac{1}{2}\Delta V$</th>
<th>$I_{\text{max}}$</th>
<th>$T_{\text{mb}}$</th>
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<tr>
<td>OH 1665 MHz</td>
<td>12.9</td>
<td>6.2</td>
<td>2.1</td>
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</tr>
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<td>OH 1612 MHz</td>
<td>25.5</td>
<td></td>
<td>15±3</td>
<td></td>
</tr>
<tr>
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<td>15±1</td>
<td>15±3</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>CO 115 GHZ</td>
<td>14±3</td>
<td>?</td>
<td>$\sim 0.07$</td>
<td></td>
</tr>
</tbody>
</table>

Emission in the CO (J=2—1) line was detected in August 1990, using the IRAM 30 m telescope at Pico Veleta (Spain). The HPBW of the instrument was $\sim 13''$ at 230 GHz. The aperture and beam efficiencies are 0.27 and 0.45, respectively. The system temperature was rather high ($\sim 8000$ K) due partly to low elevations ($\lesssim 20^\circ$). The backend consisting of a filter bank gave a velocity resolution of 1.3 km s$^{-1}$. The main beam brightness of the source was $T_{\text{mb}} = 1.3$ K.

The CO (J=2—1) line was observed using the JCMT at Mauna Kea, in December 1990. The telescope’s HPBW was $\sim 22''$ at 230 GHz. The beam efficiency $\eta_{\text{mb}}$ was not well-determined. We will adopt a value of $\eta_{\text{mb}} \approx 0.5$. The system temperature was $\sim 1300$ K. We used a wide band acousto-optical spectrometer (AOS) with a velocity resolution of 1.3 km s$^{-1}$. On the basis of the IRAM observation we expected the source to be detected at $T_{A}^* \approx 0.15$ K. The actual intensity measured was $T_{A}^* = 0.5$ K, however. This suggests that the source was resolved in the 13'' beam of IRAM. The JCMT CO (J=2—1) line profile is shown in Fig. 4.5.

We observed the object in the CO (J=1—0) line at 115 GHz in April 1991, using the 15m SEST (Booth et al. 1989) at ESO, La Silla. The telescope’s HPBW is $\sim 44''$ at 115 GHz, with a main beam efficiency of 0.7. The system temperature was 590 K. We used a wide band AOS with a velocity resolution of $\sim 0.9$ km s$^{-1}$ at 115 GHz. The observations were carried out using beam switching with a chop throw of 11.5 in azimuth. The CO (J=1—0) line was marginally detected ($S/N \sim 3$, rms noise 0.05 K at the expected velocity of the object ($V_{\text{LSR}} \sim 14$ km s$^{-1}$). Narrow (interstellar) emission was present in the reference beam at $V_{\text{LSR}} \sim 0$ km s$^{-1}$.

In Table 4.3 we list for each molecular line the derived central LSR velocity and the corresponding envelope expansion velocity. For the OH observations the latter is defined as half the distance between the top of the main maser peaks, which is a lower limit to the real outflow velocity. We also list the peak intensity of the lines. For the OH maser lines we list the average of the two polarizations (LCP and RCP) during the 1991 observations. For CO (J=2—1) the listed intensity is from the JCMT observation, using $\eta_{\text{mb}} = 0.5$. 
4.3 The nature of IRAS 17150—3224

4.3.1 The nature of the nebulosity

In the optical slit spectrum (Fig. 4.3) all Balmer lines are in absorption. There is no difference in relative intensity of these lines at a position 1.3" from the core (in the adjacent pixel row) compared to the lines in the core. A significant fraction of the intensity at 1.3" from the core is due to spill-over from the central part, but any strong nebular emission lines would at least partially fill in the absorption lines. No emission-lines are present in the weaker part of the nebula further from the core. The luminosity of the nebula on the CCD images varies smoothly over the wavelength bands from $B$, $V$, $R$ to $I$, also indicating that no strong nebular emission lines are present. We thus find no evidence that the nebular emission is due to ionized gas.

The most reasonable explanation is that the nebulosity is a compact reflection nebula surrounding the star. The fact that scattering is greatly reduced at infrared wavelengths explains why no nebula is visible in the $K$-band image. The nebula has a remarkable property: in all optical wavelength bands the ratio of core intensity of the fainter lobe to core intensity of the brighter lobe is similar: $0.35 \pm 0.03$ (the core of the fainter lobe is defined as the 4 pixels at the position of the secondary peak in the $B$ image). This is easily explained if the two lobes have point symmetry with respect to the central illuminating source, but a conspiracy of geometrical and dust scattering properties would be needed to yield such a result if the illuminating source were coincident with one of the lobes. We thus arrive at a picture where the central star is situated between the lobes. A dust torus inhibits a direct view of the central star, but through the opening at the poles the circumstellar dust shell (which may well be spherical) can be illuminated. The extinction caused by the dust torus decreases with increasing wavelengths, which explains why the intensity gap between the two lobes in the $B$-band image is progressively filled in at longer wavelengths.

The integrated flux (from 0.4 $\mu$m to 1.1 mm, integrating the SED using linear interpolation in $S_{\lambda}$) of IRAS 17150—3224 is $6 \times 10^{-11}$ W m$^{-2}$. Assuming that the star is in the post-AGB phase (see next section), and adopting a characteristic post-AGB luminosity $L = 6000 \ L_{\odot}$, we derive a distance of 1.8 kpc. This is in line with calculations by Hu and Tang (1990), who show that for distances up to $\sim 3$ kpc a compact reflection nebula may be visible around PPNe. The derived distance, combined with the angular extent of the reflection nebula of about 10", yields a linear projected extent of the nebula of $\sim 3 \times 10^{17}$ cm. This is typically the size of the circumstellar dust shell in the AGB phase.

4.3.2 Evolutionary status

It is quite unlikely that IRAS 17150—3224 is a young, massive supergiant. At an average luminosity for a young G2 supergiant of $3 \times 10^4 \ L_{\odot}$ its galactic latitude would imply a height above the galactic plane of 210 pc, which is more than two supergiant scale heights. The presence of OH 1612 MHz maser emission, the double-peaked line profile at 1667 MHz and the width of the CO profile are reminiscent of the expanding envelope of an evolved star.
4.4. OH maser emission and magnetic field

The G2I spectrum of IRAS 17150–3224 indicates that the star is in the post-AGB phase. Its progenitor was probably an intermediate mass star. This is suggested by both the low galactic latitude (a typical post-AGB luminosity $L = 6 \times 10^3 L_\odot$ yields $z = 90$ pc) and the fact that the stellar velocity is close to the general galactic velocity. In the direction of the object ($l = 353^\circ.8$, $b = 3^\circ.0$), the galactic HI velocity is between 0 and 20 km s$^{-1}$ (within 3 kpc from the sun, Brand 1986). We derive a stellar velocity $V_{\text{LSR}} = 14$ km s$^{-1}$ from the OH 1667 MHz maser and from the CO ($J=2-1$) observations. Stars of intermediate mass are expected to evolve through a planetary nebula phase. The very large infrared excess of IRAS 17150–3224 shows that enough circumstellar material is present to form a planetary nebula, once the central star has become sufficiently hot to ionize its environment. We thus identify IRAS 17150–3224 as a proto-planetary nebula. Its bipolar shape in the optical images makes it look similar to PPNe such as Roberts 22 or CRL 2688 (‘the Egg-nebula’), but its G-type spectrum shows it is in an earlier stage of evolution.

4.4 OH maser emission and magnetic field

4.4.1 OH emission

The 1667 MHz maser shows a classical double-peaked spectrum, similar to the 1612 MHz spectrum commonly observed in evolved OH/IR stars. The overall shape of the spectrum is typically that of an expanding, spherically symmetric circumstellar shell (see e.g. Reid et al. 1977). The velocity in the maser lines may be a few km s$^{-1}$ less than the terminal velocity in the CO ($J=2-1$) profile, but the difference is within the observational errors. The main peaks in the maser spectrum show no circular polarization. A few low-intensity emission features between the peaks are strongly polarized. These polarized emission features (notably the ones at 4 and 7 km s$^{-1}$) are present in the 1991 as well as in the 1990 observations.

The 1612 MHz maser, which also shows no circular polarization, has quite a remarkable spectrum. In the low-resolution spectra taken in 1990 a single masing spike is present, nearly at the velocity of the redshifted 1667 MHz peak. At the velocity of the blueshifted 1667 MHz peak no emission is observed (r.m.s. noise 0.05 Jy). The spectrum is reminiscent of the OH 1612 MHz spectrum observed in some H II regions. Interferometer maps of those objects show that such spikes originate from a single masing spot rather than from an extended region (e.g. Zijlstra et al. 1990). In the higher-resolution spectra taken in 1991 the spike is resolved into a number of individual components (Fig. 4.4a,b). The outermost emission feature at $V_{\text{LSR}} = 25.8$ km s$^{-1}$ coincides with the main peak of the 1667 MHz maser. A small wing is present towards lower velocities, but its intensity drops much faster than that of the wing in the 1667 MHz spectrum.

The 1665 MHz spectrum is rich in spikes over its whole velocity range and exhibits strong circular polarization. The 1665 MHz profiles cover a velocity range only half that of the 1667 MHz spectrum, suggesting that the 1665 MHz line is formed in a region closer to the star, where a significant velocity gradient is present (Nguyen-Q-Rieu et al. 1979). Note that the maser spectrum shows broad wings at (projected) expansion velocities in excess of the main peak velocity (the same holds to a smaller extent for
the 1667 MHz maser). This is expected in case of a velocity gradient over the masing region.

A velocity gradient in the masing region can give rise to multiple components in OH maser spectra, as well as circular polarization in the individual components (Nedoluha and Watson 1988). An alternative possibility to form multiple components is an irregular density distribution (clumps) in the wind (Cook 1966). Against this scenario Deguchi and Watson (1986) argue that it may require an unrealistic high number of chance superpositions of the clumps in order to produce strong circular polarization (magnetic fields and Doppler shifts of different clumps must match to amplify one Zeeman component, but not the other). Comparison of the 1990 maser spectra with the 1991 observations show the 1665 MHz profile to be variable. This suggests at least some degree of clumpiness in the flow. According to Alcock and Ross (1986) this is a common feature of the stellar wind from OH/IR stars.

A velocity gradient over the masing region can also explain why the 1667 MHz transition is the dominant one, and not the 1612 MHz transition (as in OH/IR stars). The 1612 MHz and the 1667 MHz maser share the same lower energy level. Usually the 1667 MHz maser is quenched when the 1612 MHz maser saturates (Field 1985). The 1612 MHz maser needs the longest amplification pathlength (Bujarrabal et al. 1980, Field 1985). In IRAS 17150–3224 the velocity gradient is apparently too large for the 1612 MHz maser to amplify, except in a few clumps where conditions happen to be favorable. Without pumping of the available molecules into the 1612 MHz transition, the 1667 MHz maser is free to operate.

The observations presented above suggest that a considerable velocity gradient is present in the outflow from IRAS 17150–3224, at large distances from the star. In principle it is possible to solve the radiative transfer equations and actually derive the velocity gradient. This is however beyond the scope of this paper. Interferometer mapping of the masers is required for detailed study of the dynamics of the outflow.

4.4.2 Magnetic field

The only known mechanism to produce circular polarization in astrophysical masers is Zeeman splitting in a magnetic field (e.g. Deguchi and Watson, 1986). Polarization can occur if the Zeeman splitting is larger than the line width (natural, thermal or microturbulent) of the maser transition. Linewidths as narrow as 0.1 km s\(^{-1}\) can be expected in OH masers around evolved stars (Cohen et al. 1987).

In our OH 1665 MHz spectra we find for a number of spikes a systematic velocity difference between the LCP and the RCP spectra, \(v_{\text{RCP}} - v_{\text{LCP}} \approx 0.14 \pm 0.07 \text{ km s}^{-1}\). This corresponds to a magnetic field strength \(B \approx 0.3 \pm 0.15 \text{ mG}\). From the derived magnetic field strength in the masing region one can make an order of magnitude estimate of the magnetic field at the stellar surface. For a magnetic dipole field, the magnetic field strength varies with distance as \(r^{-3}\). If a small fraction of ionized material is present in the stellar wind, the magnetic field lines can be frozen in the wind, and the field strength varies with \(r^{-2}\). The magnetic field will only be frozen in
4.5 Mass loss

4.5.1 CO emission

We use the CO ($J=2-1$) line observed at the JCMT to estimate the mass loss rate. The CO ($J=1-0$) spectrum does not have a high enough signal-to-noise ratio to allow a reliable determination (the same is true for the CO ($J=1-0$) spectrum obtained by Zuckerman and Dyck 1986 (Zuckerman, private communication)). We assume that the CO envelope is unresolved and use the formula derived by Knapp and Morris (1985), as modified for the $J = 2 - 1$ transition by Olofsson et al. (1990). From our CO ($J=2-1$) spectrum, we derive a main-beam brightness temperature of $\sim 1.0$ K and an expansion velocity of $\sim 15$ km s$^{-1}$. With a beam width of 22", a source distance of 1.8 kpc and a CO/H$_2$ abundance of $3 \times 10^{-4}$ (Knapp and Morris 1985), we obtain mass loss rate $\dot{M} \sim 4 \times 10^{-5}$ M$_\odot$ yr$^{-1}$.

4.5.2 Circumstellar dust

An independent estimate of the mass loss rate follows from radiative transfer modelling of the infrared emission from the circumstellar dust shell. The model also provides an estimate of the time elapsed after mass loss on the AGB terminated. We use a radiative transfer code developed by M.A.T. Groenewegen at the Astronomical Institute of the
University of Amsterdam. This code can handle a variety of spherically symmetric dust density distributions (details of this code will be discussed in a future publication). Our ‘standard model’ for IRAS 17150–3224 has \( L = 6 \times 10^4 L_\odot \), \( T_{\text{eff}} = 5200 \text{ K} \), and a dust to gas ratio (by mass) \( f = 1/100 \). After extensive test calculations using different dust properties (from Draine and Lee 1984, Bedijn 1986, Volk and Kwok 1989) we found that the dust properties of Draine and Lee provided the best fit to the IRAS observations. In order to fit the large intensity contrast between the IRAS infrared and the near-infrared it was found necessary to considerably increase the near-infrared dust absorptivity. A ratio of \( Q_{\text{abs}}(1 \mu m)/Q_{\text{abs}}(9.5 \mu m) = 1.65 \) was needed to account for the intensity contrast. For wavelengths \( \lambda \leq 7.5 \mu m \) we adopted a complex index of refraction \( m = 1.55 - 0.1i \) (Jones and Merrill 1976). The absorptivity of the Draine and Lee dust was subsequently scaled to yield \( Q_{\text{abs}}(1 \mu m)/Q_{\text{abs}}(9.5 \mu m) = 1.65 \).

As discussed in the next section, the assumption of spherical symmetry is probably justified except in the innermost regions of the circumstellar envelope. The presence of a dust torus close to the star mainly influences the optical and near-infrared radiation. A large effect on the far-infrared emission is not expected. The optical fluxes, and possibly the shorter-wavelength near-infrared fluxes as well, are probably largely due to radiation scattered from the pole of the dust torus close to the star. Since all fluxes shortward of 3.6 \( \mu m \) may be affected by scattering we consider these as upper limits.

An conspicuous feature of the spectral energy distribution of IRAS 17150 – 3224 is the steep spectral slope at wavelengths below 20 \( \mu m \), see Fig. 4.6. This is a clear indication of a cool, detached dust shell, without significant amounts of hot dust. Trial calculations show that if any post-AGB mass loss is present, the post-AGB mass loss rate must be \( \lesssim 0.05\% \) of the AGB mass loss rate. In our modelling of the source we only consider the simple situation of a constant mass loss rate on the AGB, which abruptly ends without further post-AGB mass loss.

The best fit model to the data for \( \lambda \geq 3.6 \mu m \) (using the shorter wavelengths as upper limits) is shown in Fig. 4.6. In order to match the slope of the energy distribution between 3.6 \( \mu m \) and 20 \( \mu m \), the dust must have a temperature of \( \sim 300 \text{ K} \) at the inner boundary of the dust shell. Using the expansion velocity of CO, \( V_{\exp} \sim 15 \text{ km s}^{-1} \), we find that the AGB mass loss has ceased \( \sim 65 \text{ yr} \) ago. This short timescale is however not in agreement with the fact that on the Palomar sky survey plates (taken in the nineteen-fifties) the object looks similar as it does now, while about 30 years ago the dust optical depth should have been a factor \( \sim 2 \) higher. If we adopt the expansion velocity of the OH 1665 MHz emission, \( V_{\exp} \sim 6 \text{ km s}^{-1} \), the time after mass loss stopped is \( \sim 160 \text{ yr} \). This value seems not unreasonable. It implies that the velocity difference between the OH 1665 MHz maser and the OH 1667 MHz maser (or the CO emission) is not due to a projection effect, but that a velocity gradient is indeed present.

The AGB mass loss rate derived from the model is \( \dot{M}_{\text{AGB}} \sim 7 \times 10^{-5} M_\odot \text{yr}^{-1} \) (using \( V_{\exp} = 6 \text{ km s}^{-1} \)). This is somewhat higher than derived from the CO emission, but well within the intrinsic uncertainties (at least a factor of two) of the models.
4.6 Asymmetry of the circumstellar envelope

The morphology of the reflection nebula seen in the optical images (Fig. 4.2) is clearly non-spherical. As explained in Sect. 4.3.1, the optical observations can be understood by assuming the presence of a dust torus around the star.

The question arises in which evolutionary phase this dust torus was formed: all along the AGB, at the very end of the AGB, or in the post-AGB phase? A statistical argument argues against the first possibility. Nearly all OH/IR stars have a more or less spherically symmetrical gas/dust shell, with only a few exceptions which may already be in the post-AGB phase (Chapman 1988 and references therein). In our relatively small PPN candidate sample (62 sources, of which ~ 25% without an optical counterpart), three (maybe four) objects show a compact asymmetrical reflection nebula. From the apparent lack of energy balance between optical and infrared flux in many objects it is expected that their circumstellar envelopes are non-spherical as well. Also, when one regards other, known bright PPNe, a remarkable high fraction of sources shows bipolarity (e.g. CRL 618, CRL 2688, Roberts 22), contrary to the OH/IR stars.

In the case of IRAS 17150−3224, we may obtain significant information from the OH maser emission. The classical double-peaked profile of the OH 1667 MHz maser is reminiscent of the spherical outflow from OH/IR stars. The wings in the profile towards low projected expansion velocity are difficult to understand if the maser were located in a torus, rather than in a spherical shell. The estimate of the location of the maser from Sect. 4.4.1, in combination with an expansion velocity $V_{\text{exp}} \sim 10 \text{ km s}^{-1}$, yields a travel time of ~ $10^3 \text{ yr}$ from star to masing region. With a canonical lifetime of the OH/IR star phase of $10^4 \text{ yr}$ this means that the asymmetry can only have
developed within the last 10% of the OH/IR star phase.

What can have been the cause for the transition from spherical to non-spherical geometry? Possibly the transition is linked with the contraction of the star when it evolves off the AGB. During the increase in surface temperature from $T_{\text{eff}} \sim 2500$ K on the AGB to $T_{\text{eff}} \sim 5000$ K at present, the stellar radius has decreased by a factor of four. The winds from AGB stars are generally assumed to be driven by radiation pressure on dust grains. The condensation radius remains more or less stationary while the star shrinks (assuming the dust condensation temperature remains the same). With more time needed to reach the condensation radius the gas may settle down in a disk-like configuration before condensation. This may happen due to orbital motion in a binary system, or due to magnetic confinement. For the latter, consider again Eq. 4.1 (Sect. 4.4.2). When the gas escaping from the stellar surface cools, and when there is no driving force to provide a large expansion velocity the magnetic energy density can be comparable to the gas kinetic energy for a magnetic field strength and mass loss rate as derived above.

4.7 Conclusions

The cold infrared source IRAS 17150–3224 is a proto-planetary nebula. Its spectral type is G2I, indicating that it is a relatively young PPN. From radiative transfer modelling we derive an age of $\lesssim 150$ yr after termination of the AGB wind. The mass loss rate on the AGB was large, $M \sim 4 \times 10^{-5} M_\odot$ yr$^{-1}$.

The optical image shows a bipolar reflection nebula. The optical observations indicate the presence of a dust torus which inhibits a direct view of the central star, but allows illumination of the reflection lobes. The OH 1667 MHz maser profile suggests that at large distances from the star the envelope is more or less spherical.

The OH maser spectra suggest an appreciable acceleration of the stellar wind over the masing regions. A large degree of circular polarization is present in the OH 1665 MHz maser. This polarization arises from a geometrically diluted, originally quite strong stellar magnetic field, which (at the location of the maser) must be frozen into the wind. A magnetic field strength of the order of 0.2 kG on the stellar surface (when the star was still on the AGB) is required to account for the polarization. It is argued that upon the transition from AGB to post-AGB the magnetic field may have become capable of dominating the gas motions.

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