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Optical and infrared observations of two type-II OH/IR sources *

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Summary. Optical and infrared, photometric and spectroscopic observations of two type-II OH/IR sources, OH/IR 17.7 − 2.0 and OH/IR 286.50 + 0.06, are presented. The first object is shown to be non-variable, or only slightly variable. The central star is probably of spectral type K 1–K 4, and embedded in a non-spherical shell of dust. It appears to be in an intermediate stage between the Asymptotic Giant Branch and the Planetary Nebula ones. The second object, OH/IR 286.50 + 0.06, is variable with a period near 600 days. At maximum, it has a spectral type M9. If at a distance of 8.3 kpc, its total luminosity is 1.5 $10^5\,L_\odot$, and its mass loss rate 1.5 $10^{-5}\,M_\odot\,\mathrm{yr}^{-1}$. It appears to be an extreme member of the Mira class, at the upper end of the Asymptotic Giant Branch.

Key words: planetary nebulae – stars: long-period variables – stars: OH/IR

1. Introduction

OH/IR stars are characterized by the coincidence of a type-II OH maser emission with an infrared source. The 1612 MHz maser line presents a double peaked structure indicative of an expanding envelope. The IR source is produced by thermal emission of dust in a thick circumstellar envelope heated by the central star. These objects are usually invisible in the optical range and, consequently, almost no observational data on the central sources are available. Nevertheless, similarities in the OH and IR properties with Miras or supergiants have led to the implications that the central objects are evolved stars of mass ~2–13 $M_\odot$, effective temperature ~2000–3500 K, total luminosity ~10^3–$10^5\,L_\odot$, period ~500–2000 days and mass loss rate ~10^{-6}–$10^{-4}\,M_\odot\,\mathrm{yr}^{-1}$ (Engels et al., 1983; Jones et al., 1983; de Jong, 1983). They are supposed to be in the latest stages of their evolution on the Asymptotic Giant Branch (AGB), or core-helium burning supergiants.

Some of them, associated with the reddest IR sources, showing little pulsation, but important mass loss rates ($10^{-4}\,M_\odot\,\mathrm{yr}^{-1}$ or more), could be progenitors of planetary nebulae; the prototype of such objects would be OH/IR 17.7–2.0 (Olnon et al., 1984). In this particular case, Le Bertre et al. (1984, hereafter referred to as Paper I) note a similarity between its infrared broad-band energy distribution and that of bipolar nebulae (BPN), and suggest that this object could be an OH/IR BPN. As BPN could be progenitors of planetary nebulae (e.g. Kwok and Bignell, 1984), these two interpretations may not be contradictory. Furthermore, Sèvre (1984) found on Schmidt plates a possible optical counterpart of OH/IR 17.7–2.0. Under these conditions, it appeared necessary to reinvestigate the case of this source, by means of optical and infrared observations. A preliminary report of this investigation has been presented by Le Bertre (1986, henceforth Paper II). This OH/IR star is referred to, in the literature, as: OH 17.7–2.0, OH/IR 17.7–2.0, RAFGL 5497, IRAS 1827–145 P01 and IRAS 18276–1431. The designation OH/IR 17.7–2.0 will be adopted hereafter.

In general, the invisibility of OH/IR stars is not intrinsic, but rather observational. To facilitate optical observations of these variable stars, a monitoring of selected sources has been initiated; this allows to choose favourable phases for attempting optical observations. It has, thus, been established that OH/IR 286.50 + 0.06 was at maximum around June 1986. As this source appears to be more typical than OH/IR 17.7–2.0, its observational study, made with the same techniques, is presented here for comparison. The OH maser has been discovered by Caswell et al. (1981) and the IR source by Epchtein and Nguyen-Q-Rieu (1982). This object is also known as IRAS 10379 − 5817.

2. Optical identification and positions

2.1. *OH/IR 17.7–2.0*

The radio position has been measured by Bowers et al. (1981), using the Very Large Array (VLA), with an accuracy of ±1″ (Table 1a). The Infrared Astronomical Satellite (IRAS) has detected a (10–100 μm) source whose position is also given (Beichman et al., 1985); due to the scanning mode of observation, the position uncertainty is represented by an ellipse of semi-axes 31″ and 5″, and position angle 87°. Sèvre (1984) found, on Palomar plates, an optical object coincident with the radio source that will be referred to as Object A. Very nearby (~20″ south of A), there is a bright star (Object C). The positions of A and C have been measured using the Optronics machine at ESO-Garching. Perth 70 astrometric stars (Høg and Von der Heide, 1976) were used as references and the measurements were reduced using standard ESO software; the resultant positional accuracy is estimated to be better than ±1″. In Paper I, a position was given, measured at 2.2 μm, which is about 3″ north of A. Using the ESO 1-m telescope, also at 2.2 μm, and by offsetting from C to the infrared source, a new infrared position has been determined, with an accuracy of ±2″ (Table 1a).

All infrared and radio positions are consistent with object A being a potential optical-counterpart of OH/IR 17.7–2.0.

* Based on observations obtained at ESO, La Silla, Chile

Table 1a and b. Coordinates of the OH/IR sources and nearby stars. **a** OH/IR 17.7 − 2.0. **b** OH/IR 286.50 + 0.06

Table 1a

OH/IR 17.7 − 2.0	(1950.0)	(1950.0)	Ref.
OH (1612 MHz) VLA	$18^h27^m39^s.77$ (± 1″)	−14°31′03″.9 (± 1″)	Bowers et al. (1981)
IR (10–100 μm) IRAS	18 27 40.0 (± 31″)	−14 31 05. (± 5″)	IRAS Point Source Catalogue
Palomar R: A	18 27 39.70 (± 1″)	−14 31 02.2 (± 1″)	This work
Palomar R: C	18 27 39.81 (± 1″)	−14 31 26.3 (± 1″)	This work
IR (2 μm) ESO 1 m	18 27 39.9 (± 5″)	−14 30 59. (± 5″)	Paper I
IR (2 μm)	18 27 39.8 (± 2″)	−14 31 05. (± 2″)	This work

Table 1b

OH/IR 286.50 + 0.06	(1950.0)	(1950.0)	Ref.
OH (1612 MHz) Parkes	$10^h38^m09^s.6$ (± 35″)	−58°17′48″ (± 35″)	Caswell et al. (1981)
IR (2 μm) ESO 1 m	10 37 59.7 (± 7″)	−58 17 41. (± 7″)	Epchtein and Nguyen-Q-Rieu (1982)
IR (10–100 μm) IRAS	10 37 58.2 (± 8″)	−58 17 23. (± 13″)	IRAS Point Source Catalogue
IR (2 μm) ESO 1 m	10 37 59.6 (± 5″)	−58 17 40. (± 5″)	This work
Nearby Star (S) ESO R plate	10 37 59.43 (± 1″)	−58 17 40.4 (± 1″)	This work
CCD frames Danish 1.5 m	10 37 59.76 (± 2″)	−58 17 38.4 (± 2″)	This work

2.2. OH/IR 286.50+0.06

In Table 1b, the OH position determined by Caswell et al. (1981), the IR position, at 2 μm, by Epchtein and Nguyen-Q-Rieu (1982), and the (10–100 μm) position, by Beichman et al. (1984), are given. The Epchtein and Nguyen-Q-Rieu position has been corrected for a printing error (Epchtein, 1984). Using the ESO 1-m telescope, the position, at 2 μm, has been remeasured. Inspection of the ESO Blue and Red plates led to no convincing optical candidate. The position of the most nearby star (S) is given in Table 1b.

CCD frames in the Johnson V, R and Gunn i, z filters were obtained at the 1.5-m Danish telescope at La Silla, on 1986 March 31. A red source was apparent a few arcseconds north-east of the previous star (S); it was not possible to see it on the V frame, whereas it was the brightest of the field on the z frame. Its position, measured on CCD frames relatively to star (S), is given in Table 1b.

This source appears to be the counterpart of the IR object discovered by Epchtein and Nguyen-Q-Rieu (1982). Although its position deviates from the radio one by twice the rms (σ) error (Caswell et al., 1981), it is very probably related to the OH maser. Epchtein and Nguyen-Q-Rieu have not found any other red ($K-L>1.5$) source in the 3σ error box of Caswell et al.; also, this error box shows no IRAS source other than IRAS 10379−5817. Furthermore, the probability that a background star of magnitude $L\sim 2-3$ lies within 80″ of a type II OH maser is near 0.0 (Gehrz et al., 1985). Finally, its physical properties (see below: Sect. 5.2) are typical of those expected for an OH/IR source.

3. Photometric observations

Broad-band photometric data has been obtained using the ESO 1-m telescope, equipped with its standard photometers, on both sources, between 1984 and 1986.

3.1. OH/IR 17.7 − 2.0

(J, H, K, L, M) data have been acquired at three different epochs and are presented in Table 2, together with the results obtained in 1983 with the same instrument (Paper I). Observations were performed also in September 1984, but with an instrumental setting which did not prevent contamination by a nearby star, and, therefore, have been disregarded. Although the sampling is loose, it can be concluded that, within error bars, there is no variation. Also, the (L, M) magnitudes obtained in this work are in agreement with those obtained by Herman (1983) in June 1982 (7.06 and 5.90, respectively).

Date in the range (0.4–0.8 μm) and (10–20 μm) were also acquired in June 1985; the former are given in the Cousins system. The broad-band spectrum resulting from the June 1985 observations is presented in Fig. 1. As the source does not appear to be variable, it is meaningful to complete these data with the IRAS ones, and to derive, thus, the (0.4–100 μm) energy distribution; IRAS data have been corrected assuming a colour temperature, $T_c = 150$ K.

Table 2. OH/IR 17.7 − 2.0 photometric data. Results for 25-09-83 are as in Paper I

Epoch	U	B	V	R	I	J	H	K	L	M	N	N1	N2	N3	QO
1983 Sept. 25						11.64 ±0.20	10.63 ±0.15	9.35 ±0.10	7.21 ±0.20	5.85 ±0.30	1.28 ±0.20				
1985 June 2						11.61 ±0.05	10.56 ±0.05	9.35 ±0.05	7.01 ±0.10	5.62 ±0.20	1.26 ±0.10	2.57 ±0.20	1.92 ±0.20	−0.26 ±0.25	−2.07 ±0.30
1985 June 7	17.13 ±0.40	16.12 ±0.20	14.63 ±0.05	13.74 ±0.05	12.94 ±0.05										
1986 Apr. 12						11.52 ±0.08	10.50 ±0.05	9.30 ±0.05	7.02 ±0.15	5.91 ±0.30					
1986 Aug. 28						11.45 ±0.06	10.49 ±0.05	9.32 ±0.06	6.94 ±0.15	5.93 ±0.30					

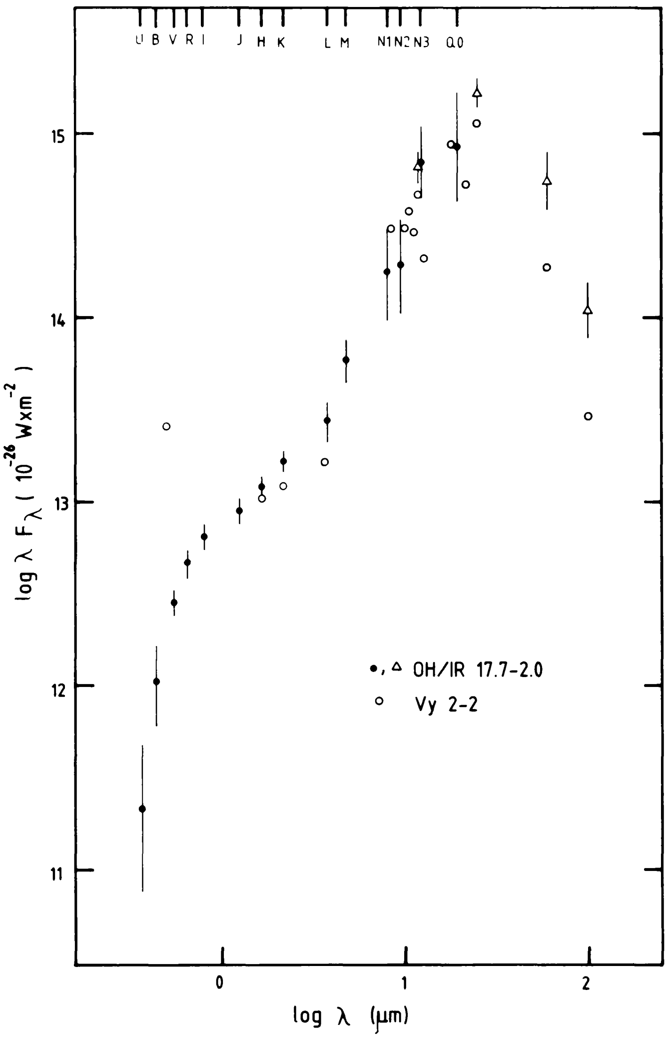

Fig. 1. Broad-band energy distribution of OH/IR 17.7 − 2.0: ● data obtained at the ESO 1-m telescope in June 1985; △ IRAS data. The empty circles (○) correspond to the energy distribution of Vy 2–2 (see Sect. 5.1)

3.2. *OH/IR 286.50 + 0.06*

(J, H, K, L, M) light curves are presented in Fig. 2; they appear to be slightly asymmetrical. It can be seen that the object is variable with a period 550–600 days. Epochs and magnitudes of extrema have been determined by second-order polynomial least-square fits; measurements have been weighted with the inverse square of the errors. For the minimum, data between Julian Date (JD) 2446199 and 2446477 have been used, whereas, for the maximum, data between JD 2446460 and 2446671 have been used. Results are given in Table 3. The source appears to be redder at minimum than at maximum: J–K being ∼5.3 at minimum and ∼3.9 at maximum. The light curve amplitude decreases with increasing wavelengths and there is a tendency for extrema to occur earlier at longer wavelengths.

(10–20 μm) measurements were obtained in June 1985 (JD = 2446221), approximately half way between minimum and maximum, and are presented in Fig. 3. On the same figure, the IRAS data, corrected for a colour temperature of 600 K, have also been plotted. They appear to have been obtained at a phase

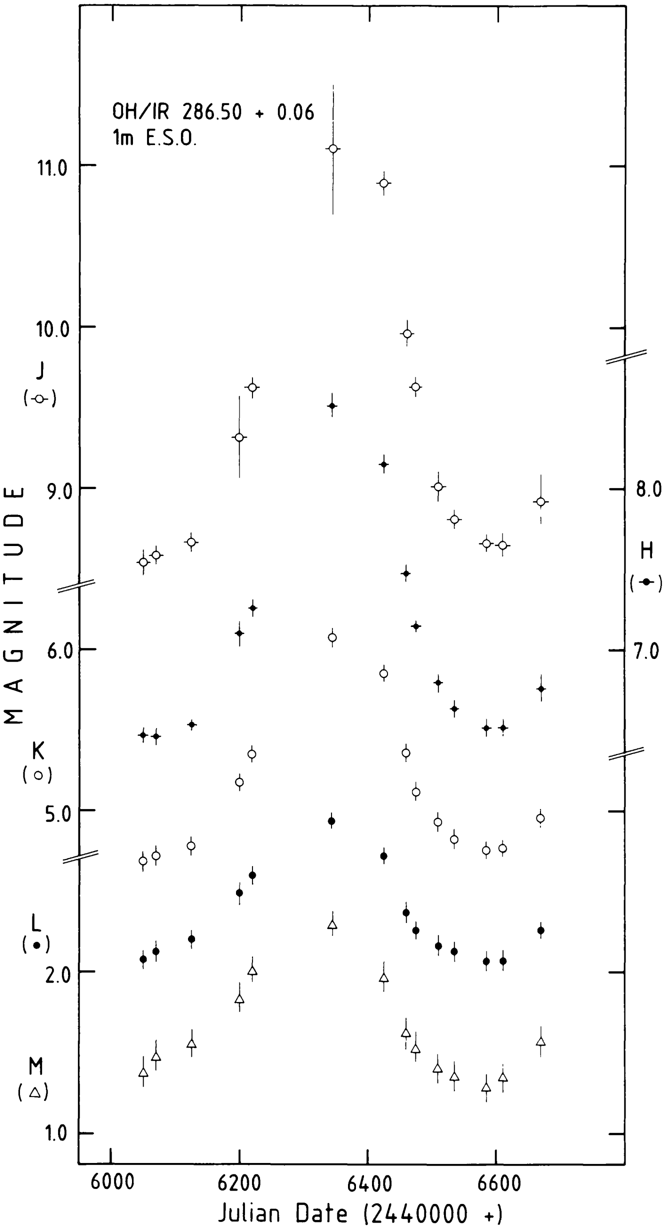

Fig. 2. (*J*, *H*, *K*, *L*, *M*) light curves of OH/IR 286.50 + 0.06 obtained between December 1984 and August 1986

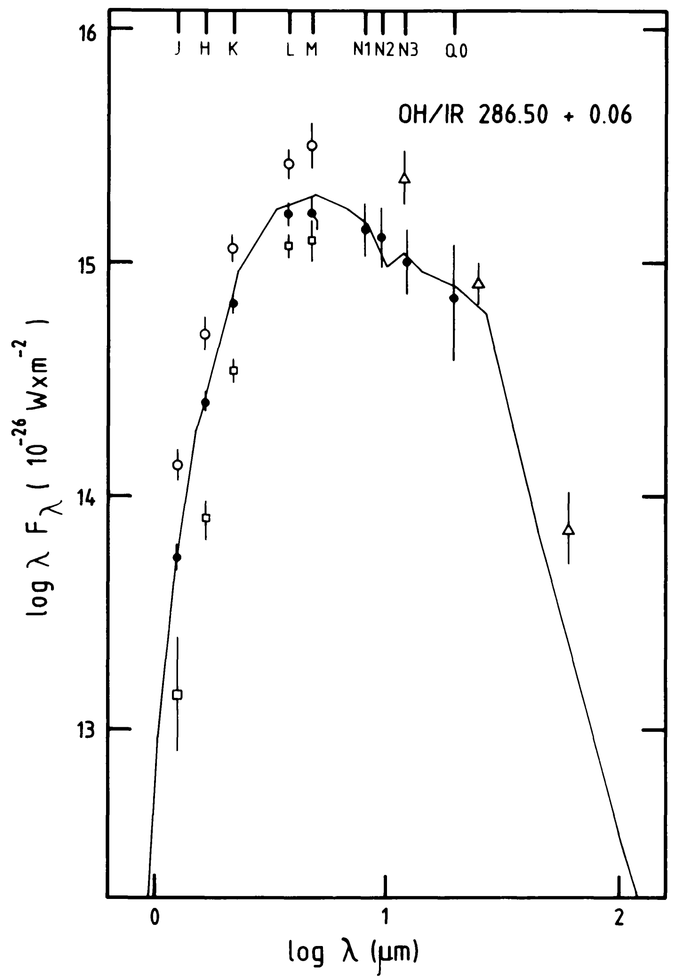

Fig. 3. Energy distribution of OH/IR 286.50+0.06: ●: data obtained at the ESO 1-m on 1985 June 4; □: on 1985 September 29 (minimum); ○ on 1986 June 2 (maximum); △: IRAS data. The solid line corresponds to an adjustment discussed in Sect. 5.2

Table 3. Parameters of the OH/IR 286.50+0.06 light curves. To get Julian Date, add 2440000 to the epoch

		J	H	K	L	M	$J-K$
Min.	Magn.	11.48	8.58	6.17	2.96	2.32	5.31
	Epoch	6348	6345	6340	6327	6319	–
Max.	Magn.	8.61	6.47	4.73	2.07	1.30	3.88
	Epoch	6592	6590	6587	6577	6570	–
Light curve amplitude		2.87	2.11	1.44	0.89	1.02	–

representative of the OH/IR source maximum; there is no 100 μm data due to confusion with neighbours and to extended galactic emission.

4. Spectroscopic observations

4.1. OH/IR 17.7–2.0

Object A was first observed on 1985 March 10/11, using the ESO 1.5-m telescope equipped with a Boller and Chivens spectrograph and a dual channel IDS detector. The twin decker apertures were set to 4″ × 4″ each, both beams being 30″ apart. Spectral range was 4200–7500 Å and resolution ~15 Å (Paper I). A second spectrum was acquired on 1985 September 1/2, at the 3.6-m telescope equipped with a similar spectrograph, but a CCD array detector used in the long-slit mode. This observing mode allows a safer cancellation of sky background which is of importance in this particular case, where the field is very crowded. Five elementary spectra were acquired with different orientations of the slit; the resulting spectrum (Fig. 4a) has been obtained by averaging them.

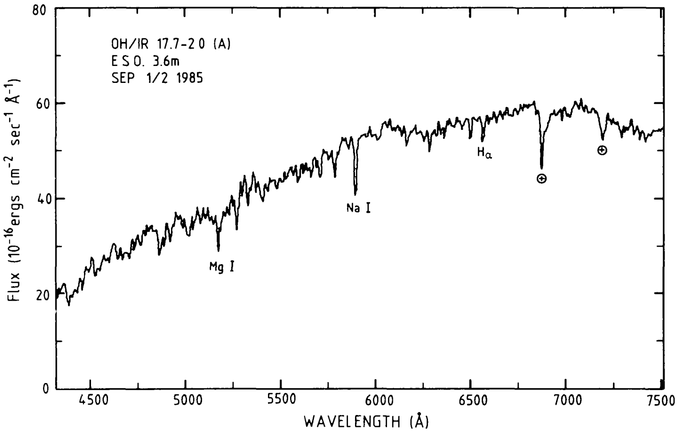

Fig. 4a. 4400–7500 Å spectrum of Object A (OH/IR 17.7 − 2.0). Spectral resolution is ~12 Å; calibration in fluxes is accurate to ~30%. A few absorption features are indicated

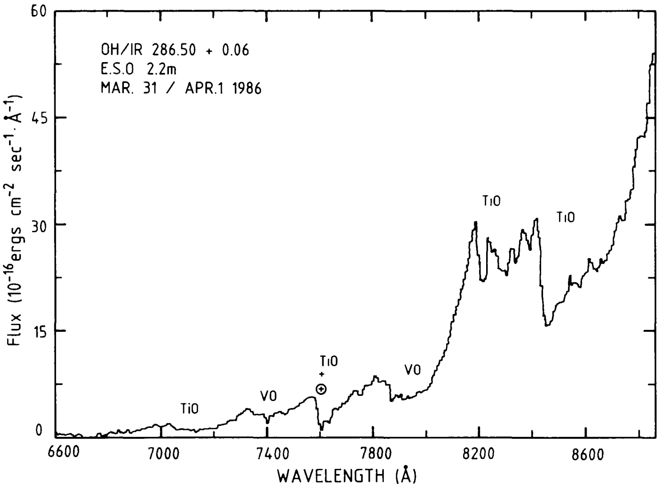

Fig. 4b. 6600–8800 Å spectrum of OH/IR 286.50 + 0.06 counterpart at maximum. Spectral resolution is ~20 Å; the spectrum has been truncated at $\lambda = 6600$ Å. Calibration in fluxes is only approximative. Some TiO and VO absorption bands are indicated

All spectra were reduced using the standard IHAP (Image Handling and Processing, Middelburg and Crane, 1979) software. Calibrations in flux were derived by using Oke (1974) and Stone (1977) standard stars and are estimated to be accurate to ~30%; in both cases they appear to be consistent with *B*, *V*, *R* data (Table 2).

In Fig. 4a, narrow absorption features are clearly seen; as most of them are present in the elementary spectra, they can be considered as real. There is no evidence for molecular absorption bands. Comparison with spectra in the library of Jacoby et al. (1984), points toward a K1–K4 giant or supergiant.

4.2. OH/IR 286.50 + 0.06

Its counterpart was observed with the 2.2-m telescope equipped with a Boller and Chivens spectrograph and a CCD array, on JD 2446521, consequently, shortly before maximum (see Fig. 2). The spectral range was 4700–8800 Å and the resolution ~20 Å. The calibration in flux was done with only one standard star, Feige 56 (Stone, 1977), and its accuracy cannot be evaluated. The spectrum is slightly contaminated by the nearby star (S) at wavelengths shorter than 7000 Å. Apart from that, it appears to be very red and dominated by TiO and VO absorption bands (Fig. 4b). The strengths of the VO features point towards an M9 spectral type (Turnshek et al., 1985).

5. Discussion

5.1. OH/IR 17.7 − 2.0

This OH source is peculiar in the sense that, although its spectrum is typical of a type-II OH maser, it presents little variation, if any (Herman, 1983). In the 10–100 μm range, the probability of variability quoted in the IRAS Point Source Catalogue is low (~20%). From the near-infrared data presented here and those of Herman (1983), there is no evidence of variability in the range 1–5 μm. Finally, spectroscopic and photometric data obtained on Source A at different epochs are consistent (cf. Sect. 4.1). However, Engels et al. (1986) find, in the direction of OH/IR 17.7 − 2.0, a variable H_2O maser emission.

In Sect. 2.1, it has been shown that Source A was spatially coincident with the OH/IR star to within relatively small error boxes (~2″). Unfortunately, as the IR source does not appear to be variable, variability study cannot be used to prove their physical association. Nevertheless, it has been reported in Paper II that the IR spectrum does not present any CO absorption at 2.3 μm. As Source A is of spectral type K1–K4, its effective temperature is around 4200 K and, thus, its spectrum, in a ν-F_ν diagram like in Fig. 1, peaks at ~0.9 μm. Consequently, if it were an intervening star, not related to the OH/IR source, it could not contribute significantly to the 2 μm flux. The absence of CO feature appears, thus, intrinsic to the central star of OH/IR 17.7 − 2.0. This means that it is of spectral type earlier than K5 (Frogel et al., 1978); as this classification is compatible with the one of Source A, it supports the physical association hypothesis.

In Paper I, it has been argued, from the 1–100 μm energy distribution similarity between GL 2688 (or other BPN) and OH/IR 17.7 − 2.0, that the latter could also be a BPN. The energy distribution, complemented by optical photometry of Source A, and presented in Fig. 1, confirms this interpretation. The optical appearance of BPN around evolved stars is probably due to scattering of light in a circumstellar cloud characterized by an axisymmetrical distribution of dust (Morris, 1981; Yusef-Zadeh et al., 1984). However, CCD images were obtained with different filters (Gunn *g*, *r*, *i*, *z*) using the 1.5-m Danish telescope at La Silla on 1986 June 20/21; on all, with the possible exception of the *z* frame, Source A presents a stellar appearance. This lack of evidence may not be conflicting with the BPN hypothesis. If one adopts the kinematical distance of 5.4 kpc, derived from the OH maser line (Bowers et al., 1981), an object of 5000 AU would present a size slightly less than 1″ and be barely resolvable. Another possible explanation is that the object is intrinsically compact. In both cases, the shape of the energy distribution would thus simply reveal an axisymmetrical structure of the dust shell. It is worth nothing that Bowers et al. (1981) have observed at 1612 MHz an elongated image (3″.1 × 1″.4).

Adopting again the kinematical distance and assuming that the object radiates isotropically (which, from above, may not be entirely correct), one finds a total luminosity ~2 $10^4 L_\odot$; this implies a supergiant luminosity class. As its spectral type is at least earlier than K5, the central star of OH/IR 17.7 − 2.0 appears to have ended its evolution on the AGB and to be evolving towards the planetary nebula stage. In that aspect, it presents some resemblance with the compact nebula Vy 2–2, which has been proposed to be intermediate between type II OH/IR sources and planetary nebulae (Davis et al., 1979). This object is coincident with an OH maser source which presents only a blue shifted emission peak. It is also a source of free-free radio continuum radiation. These facts indicate that the central star of Vy 2–2 is hot enough to ionize its inner circumstellar shell, and that there is still a neutral outer shell, remnant of the envelope ejected during the red-giant phase. The absence of the red-shifted peak has been explained by Davis et al. (1979) as due to its absorption by the central compact cloud of ionized gas responsible for the radio continuum. Adopting a symmetric interpretation, the presence, in the 1612-MHz spectrum of OH/IR 17.7 − 2.0, of the red peak indicates that the central star cannot still ionize its inner circumstellar shell and that, therefore, it is of spectral type later than B. Thus, this object would appear to be intermediate between AGB stars and stars like the one exciting Vy 2–2. For comparison, in Fig. 1, the energy distribution of Vy 2–2, derived from Perek and Kohoutek (1967), Cohen and Barlow (1974) and Beichman et al. (1983), is presented; the IRAS data have been corrected for $T_c = 190$ K. Except in the optical range, both broad-band energy distributions are similar. The fluxes at 35 μm, assumed to be responsible for the excitation of OH maser lines (Elitzur et al., 1976), are comparable, whereas the flux at 1612 MHz of OH/IR 17.7 − 2.0 (Bowers, 1978) is, at least, 10 times larger than the one of Vy 2–2 (Davis et al., 1979); this can be understood if the OH shell of Vy 2–2 has already partly disappeared. Finally, it is interesting to note that Vy 2–2 is unresolved at optical wavelengths, is not reported to be variable (VAR = 0, from IRAS Point Source Catalogue) and presents an elongated structure at 4885 MHz (Seaquist and Davis, 1983).

5.2. *OH/IR 286.50 + 0.06*

This object is variable with a period 550–600 days long and at maximum presents a spectral type M9. These results are in agreement with an extrapolation of the Type-Period relationship determined for Mira variables by Keenan et al. (1974). The central star of OH/IR 286.50 + 0.06 appears, thus, to be an extreme member of the Mira class.

The energy distribution of this source is similar to the one of other type-II OH/IR sources, such as OH/IR 285.05 + 0.07. The energy distribution of the latter has been modelled by Le Bertre et al. (1984). Using the same circumstellar dust shell (CDS) radiative transfer model, an adjustment of the average OH/IR 286.50 + 0.06 spectrum has been performed; the result is presented in Fig. 3, together with the observed data points. Between maximum and minimum, the Mira variables are changing by approximately three subtypes (Wyckoff, 1970); following Dyck et al. (1974), an average stellar effective temperature of 1600 K, corresponding to type M10, has been adopted. The temperature of the hottest grains have been set to 800 K (Salpeter, 1974). As the source is in the galactic plane, the observed energy distribution is affected by interstellar extinction. Caswell et al. (1981) give a kinematic distance of 8.3 kpc; therefore, the computed spectrum, emergent from the CDS, has been corrected for an absorption corresponding to $\tau_{10\,\mu m} = 1$ (Rieke and Lebofsky, 1985).

The CDS optical depth, at 10 μm, is derived to be 1.6. At the kinematic distance, the total luminosity is $1.5\ 10^5\ L_\odot$. Adopting for the dust shell an expansion velocity equal to the OH one, $V_e = 16\ \mathrm{km\,s^{-1}}$ (Caswell et al., 1981), the dust mass loss is evaluated to be $1.5\ 10^{-7}\ M_\odot\ \mathrm{yr}^{-1}$. For a gas to dust ratio of 100, the total mass loss rate is $\sim 1.5\ 10^{-5}\ M_\odot\ \mathrm{yr}^{-1}$. These values are representative of the OH/IR source on average (Fig. 3); actually, the luminosity changes by a factor of 2.5 between minimum and maximum.

All these properties allow to classify OH/IR 286.50 + 0.06 as a source of type VM II (Jones et al., 1983) or B (de Jong, 1983). Such objects are assumed to be evolved Miras at the top of the AGB, pulsating in the first harmonic mode, and with initial masses in the range 4–9 $M_\odot$.

6. Conclusion

Optical and infrared observations of two type-II OH/IR sources have been presented. Although it is not possible to completely rule out that Source A is a background object coincident with OH/IR 17.7 − 2.0, there is a convergence of arguments for identifying it as the optical counterpart of the OH/IR source. There is no ambiguity in the case of OH/IR 286.50 + 0.06.

OH/IR 17.7 − 2.0 is of spectral type earlier than K5, and most probably K1–K4; in any case, it is not hot enough to ionize its inner envelope. It appears to constitute a link between AGB objects and young compact planetary nebulae such as Vy 2–2. As it is not, or little, variable, it can be inferred that, in protoplanetary objects, stellar pulsations are damping out before the central star is able to ionize its circumstellar envelope; thus, oxygen-rich protoplanetary sources might be found preferentially at sites of non-variable type-II OH maser emission. The 0.4–100 μm energy distribution of OH/IR 17.7 − 2.0 supports the interpretation, developed in Paper I, that its circumstellar envelope is axisymmetric, as in bipolar nebulae.

OH/IR 286.50 + 0.06 appears to be an extreme Mira, at the top of the AGB and in a stage of intense mass loss.

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