A search for OH maser emission from post-asymptotic giant branch stars^{*}

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Abstract. — We present a survey for OH maser emission at 18 cm in the direction of 196 IRAS point sources. The primary aim of the survey was to detect OH maser emission from post-asymptotic giant branch (post-AGB) stars. OH emission and/or absorption was detected in the direction of 77 sources of which 57 OH detections were previously unknown, giving an overall detection rate of 39 per cent. Fourteen maser sources associated with evolved stars or planetary nebulae were found, corresponding to 7 per cent of the total observed. These included three planetary nebulae (two new OH detections), nine post-AGB stars (three new OH detections) and two cold OH/IR stars (both previously known). Two sources were of uncertain identification (both new OH detections). The remainder of the OH sources were identified with young stellar objects and with HII regions. The survey included the detection of OH maser emission from HD 101584, an early-type supergiant at high Galactic latitude. For several of the post-AGB stars, changes have occurred in the OH spectral profiles over a period of several years. This is interpreted as evidence for rapid changes in the stellar winds, due either to interactions with stellar companions, novae-like events or rapid stellar evolution.

Key words: masers — stars: AGB, post AGB — planetary nebulae — radio lines: stars

1. Introduction

During the last two decades, it has been recognized that mass loss through stellar winds plays an essential role in the late stages of stellar evolution. For low- and intermediate-mass stars, the largest mass-loss rates, of up to $10^{-4} M_{\odot} \text{ yr}^{-1}$, occur from long-period variable stars on the asymptotic giant branch (AGB). These include the Mira variables and OH/IR stars with stellar periods between ~ 300 and 3000 days. The end of the AGB evolutionary stage probably occurs when a significant fraction of the gas in the outer layers of the stellar atmosphere has been ejected and the star can no longer support strong radial pulsations (Volk & Kwok 1989). On the Hertzsprung Russell diagram, the star then leaves the AGB and moves on a horizontal track of constant luminosity towards higher temperatures. The effective temperature rapidly increases by a factor of ~ 100 to tempera-

tures of over 30 000 K. At such temperatures the stellar energy distribution is strongest in the far-ultraviolet. The ultraviolet radiation ionizes the remnant envelope and the star is seen as a planetary nebula with a visible central star surrounded by a glowing ionized envelope.

The evolution of stars between the AGB and planetary nebulae stages is believed to be extremely rapid, lasting at most for a few thousand years (Schnönbner 1983; Sun & Kwok 1987). During this post-AGB phase, the stellar mass-loss rate decreases greatly. The circumstellar dust shell moves away from the star and decreases in temperature from ~ 400 to 100 K (Bedijn 1987; Zijlstra et al. 1992). Strong changes are likely to occur in the envelope kinematics and morphologies. Whilst the circumstellar envelopes of asymptotic giant branch stars generally show spherical symmetry, the shapes of planetary nebulae are often strikingly axi-symmetric with less than 25 per cent showing circular symmetry (Balick 1987). The spatial structures of the envelopes of post-AGB stars are known only in a few cases but most of these appear bipolar (te Lintel Hekkert et al. 1995; Morris & Cahane 1995 and references therein).

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^{*}Table 2 is only available in electronic form; Tables 3 and 4 are also available in electronic form at CDS via anonymous ftp cdsarc.u-strasbg.fr or 130.79.128.5

AGB stars and post-AGB stars with oxygen-rich dust-shells may exhibit one or more of the OH 18-cm maser lines (e.g. Cohen 1989). The flux density ratios between the different maser lines and the shapes of the spectral profiles depend strongly on the temperatures, densities and geometries of the circumstellar dust/gas envelopes. Among the known evolved stars with OH maser emission, several objects have been recognized as possible post-AGB stars, including OH 231.8+4.2 (Morris et al. 1987 and references therein); IRAS 16342–3814 and IRAS 15405–4945 (te Lintel Hekkert et al. 1988). These three sources have almost identical IRAS colours; their far-infrared flux densities can be fitted with a 100 K (± 15 K) black body. All three have OH main-line emission at 1665 or 1667 MHz and OH satellite line emission at 1612 MHz. The maser lines have non-standard profiles and show evidence for high expansion velocities in parts of their circumstellar dust shells. These can be interpreted as evidence for a rapid change of the dust geometry from spherical to bipolar outflows (te Lintel Hekkert et al. 1992).

In this paper we describe a survey in which we searched for OH maser emission in the direction of IRAS sources selected to have infrared colour temperatures cooler than ~ 250 K. The main aim of the survey was to detect OH maser emission from stars, which on the basis of their radio and/or infrared properties, could be identified as likely post-AGB objects. In Sects. 2–4 we describe the OH survey and the results obtained. In Sects. 5 and 6 we discuss the OH maser properties of the evolved stars detected in the survey.

2. Sample selection

The sources for the survey were selected from the IRAS Point Source Catalogue (second edition), using the 12-, 25-, 60- and 100- μm flux densities (f_{12} , f_{25} , f_{60} and f_{100}). The IRAS sample selection criteria are listed in Table 1. Sources with upper limits only at 25 or 60 μm were not observed.

The infrared selection criteria were chosen to select sources with far-infrared colour temperatures between approximately 50 and 250 K. This temperature range is known to include post-asymptotic giant branch stars, some planetary nebulae and non-variable OH/IR stars but excludes evolved stars in an earlier stage of evolution. In particular the selection criteria excludes all Mira variables and carbon stars and most variable OH/IR stars (te Lintel Hekkert 1991).

In addition to selecting post-AGB candidates, the IRAS far-infrared colour selection criteria used also selects objects associated with compact HII regions, young stellar objects (YSO) and stars embedded in molecular clouds. These objects cannot be distinguished from post-AGB sources on the basis of their infrared colours alone as they share the same colour characteristics (te Lintel Hekkert 1991). In addition they are likely sources of OH

maser emission and/or OH absorption and are intrinsically far more numerous in the Galaxy than are the post-AGB stars. As shown in Sect. 4, the OH properties of the evolved stellar sources are considerably different to those associated with HII regions, or YSOs and this allows a clear separation between the different categories.

In total, 308 IRAS sources were selected using the criteria given in Table 1, covering both the northern and southern skies. Of these, 196 sources were observed in the available observing time. The survey is complete (148 sources observed) for declinations south of 0° .

Table 1. IRAS infrared selection criteria

$f_{60 \mu\text{m}}$	$> 30 \text{ Jy}$
$\log(f_{25 \mu\text{m}}/f_{12 \mu\text{m}})$	> 0.0
$\log(f_{60 \mu\text{m}}/f_{25 \mu\text{m}})$	> 0.0
$\log(f_{100 \mu\text{m}}/f_{60 \mu\text{m}})$	< 0.1

3. Observations

3.1. Parkes observations

Observations of 126 IRAS-selected sources were taken in September and October 1990 and March 1991, using the Parkes 64-m radio telescope. The telescope has a half-power beamwidth of 12.6 arcmin and a system temperature of approximately 40 K at 18 cm. The spectral bandwidth was 2.0 MHz and each source was observed in the three OH lines at central frequencies of 1612.231, 1665.402 and 1667.359 MHz. In addition, a few sources were observed in the OH line at 1720.530 MHz. For all observations, a 1024-channel autocorrelator spectrometer was split into two bands of 512 channels each, measuring the left- and right-hand circular polarizations (LHC, RHC). The velocity resolution was 0.9 km s^{-1} and the velocity range observed was from -180 to $+180 \text{ km s}^{-1}$. Absolute flux calibrations were obtained relative to Hydra A, assuming an 18-cm flux density of 18 Jy in each sense of circular polarization. The integration time per source was typically 20 min giving an rms level in the spectra of typically 50 mJy. The absolute flux densities are accurate to ~ 10 per cent.

3.2. Nançay observations

Nançay observations for 70 sources were taken in 1990 January using left-hand circular polarization only. The half-power beamwidth was 3.5 arcmin in right ascension and 18.0 arcmin in declination. The system temperature was ~ 60 K and the ratio of flux to antenna temperature was taken to be 1.1 Jy K^{-1} . The four OH transitions were observed simultaneously by splitting the 1024-channel autocorrelator into four filter banks with each bank

observing at one OH transition frequency. A frequency-switching technique was used in which each bank first observed the velocity range from -13 to $+225$ km s $^{-1}$, and then the velocity range from -180 to $+30$ km s $^{-1}$. The total velocity range covered was therefore from -180 to $+225$ km s $^{-1}$, with a velocity resolution of 0.9 km s $^{-1}$. An integration time of 20 min per source was used giving a typical rms in the spectra of 90 mJy.

4. Results and source classification

The results of the OH survey are summarized in Table 2. For the non-detections Table 2 gives the one-sigma noise levels in the spectra for each of the OH transitions observed. For sources detected in OH, the symbols E and A indicate the detection of a source in emission or absorption respectively and the symbol ** is used to denote a new OH detection. In total OH emission only was detected from 46 of the 196 sources, OH absorption towards 13 sources and both emission and absorption in the direction of 18 sources.

The OH spectra of all sources detected in emission and/or absorption are plotted in Fig. 1. In each spectrum, the OH flux density at 1612, 1665, 1667 or 1720 MHz is plotted against velocity. All velocities are given with respect to the local standard of rest. For the Parkes spectra, the OH flux densities are defined as $(\text{RHC} + \text{LHC})/2$. In addition, for sources where the circular polarization, $|(\text{RHC} - \text{LHC}) / (\text{RHC} + \text{LHC})|$, was greater than 15 per cent, the difference spectrum, $(\text{RHC} - \text{LHC})$ is also plotted. For the Nançay spectra the LHC polarization OH flux densities are plotted. Each spectrum is labelled with the IRAS name, the epoch of the observations, the quantity plotted: the OH transition (1612, 1665, 1667 or 1720 MHz) with “R-L” indicating the difference spectrum, RHC-LHC, and the Galactic coordinates corresponding to the IRAS position.

In Table 2, the sources detected in OH emission and/or absorption are classified on the basis of their OH and infrared properties, or using available information from the literature. Of the 77 detected sources, 14 are classified as evolved stars with 2 cold OH/IR stars (both previously known), nine post-AGB stars (3 new OH detections) and 3 planetary nebulae (3 new OH detections). The classification of these sources and their OH properties are discussed further in Sect. 5.

The remaining 63 sources detected in OH includes 61 sources classified as “HII” regions (with 50 new OH detections) and 2 sources of uncertain classification (both new detections). The classification as an “HII region” is used for young stellar objects, OH originating from molecular clouds and for (compact) HII regions and is based on one or more of the following criteria:

- IRAS sources associated with known HII regions. Known associations have been used wherever possible.

- previous OH detections associated with HII regions have been reported for 7 sources in our sample (Weaver et al. 1968; Caswell et al. 1980; Caswell & Haynes 1983a,b; Caswell & Haynes 1987).
- sources showing OH absorption in the direction of the IRAS positions. In HII regions, absorption of the background continuum occurs from OH molecules in the surrounding molecular clouds. As an example, see IRAS 16500–4304.
- sources showing narrow OH main-line emission, with $\Delta V < 15$ km s $^{-1}$, and a local thermodynamic equilibrium flux ratio of $F_{1667}/F_{1665} \sim 2$. In these cases the IRAS point sources are likely to be associated with ultra compact HII regions, young stellar objects (YSO) or with T Tauri stars embedded in molecular cloud complexes (Wood & Churchwell 1989). An example in this category is IRAS 12496–7650.
- sources with narrow OH emission which is strongest at 1665 MHz. The 1665-MHz emission from these sources is usually strongly polarized. These maser characteristics are associated with compact HII regions. A typical example is IRAS 10460–5811.

Note that more accurate radio positions are needed to determine whether the OH detections associated with HII regions are coincident with the IRAS positions. In at least some cases, it is likely that the OH is detected from HII regions which are not associated with the IRAS sources. As an example, consider the OH spectrum obtained towards IRAS 16168–5006 (Fig. 1). The present data show OH in two velocity regions at ~ -90 and -45 km s $^{-1}$. More accurate OH positions determined previously by Caswell et al. (1980) show that these two velocity regions correspond to two separate complexes, each separated by several arcmin from the IRAS position.

5. Classification of the evolved stars

Table 3 lists the OH detections associated with evolved stars and planetary nebulae and summarizes their OH properties. The columns of the first row of Table 3 are as follows:

- 1: IRAS name
- 2: IRAS Low Resolution Spectrograph (LRS) classification
- 3: f_{60}
- 4: epoch of observation
- 5 & 6: Galactic longitude and latitude (degrees) corresponding to the IRAS position
- 7: other names or associations, if any
- 8: source classification
- 9: references giving additional information

The columns of the second and following rows for each source in Table 3 are as follows:

- 1: OH transition

- 2: peak OH flux density measured in absorption or emission (Jy)
- 3: velocity of the strongest OH feature (km s^{-1})
- 4: median OH velocity (km s^{-1})
- 5: total velocity coverage of the OH features (km s^{-1})
- 6: circular polarization (P), if over 15% (Parkes data only)

We now discuss briefly each of the sources identified as being an evolved star.

5.1. The OH/IR stars: IRAS 17004–4119 (OH 344.93+0.01), IRAS 20272+3535 (OH 75.3–1.8)

These are both well-known OH/IR stars (Fix & Mutel 1984; te Lintel Hekkert et al. 1989 and references therein). OH 344.93+0.01 has a standard twin-peaked 1612-MHz profile with the two peaks separated by 37.8 km s^{-1} . However, the 1667-MHz profile shows an unusual plateau of emission between the two outer peaks. No emission was detected at 1665 MHz. This source belongs to a small, but well-defined group of stars which have large envelope expansion velocities and exceptionally long stellar periods. These stars are likely to have large progenitor masses of at least $4 M_{\odot}$ (Chapman et al. 1995). Long-term monitoring of the OH 1612-MHz emission from this source shows it to have a stellar period of ~ 2000 days (J.M. Chapman, private communication).

OH 75.4–1.8 appears to have standard 1612- and 1667-MHz spectral profiles. This source was not detected at 1665 MHz.

5.2. The planetary nebulae: IRAS 16280–4008 (PK 341+5.1), IRAS 17103–3702 (PK 349+1.1, NGC 6302), IRAS 17180–2708 (PK 358+5.1)

Weak 1612-MHz maser emission was discovered from PK 341+5.1 (NGC 6153) and weak 1667 MHz maser emission from PK 358+5.1. PK 349+1.1 (NGC 6302) is a well known planetary nebula with a bipolar outflow. This source was detected in emission at 1612 MHz and in absorption at 1667 MHz, confirming earlier OH detections (Payne et al. 1988; Zijlstra et al. 1989). The radio properties and evolutionary nature of young planetary nebulae, including PK 349+1.1, are discussed in detail by Zijlstra et al. (1989).

5.3. The post-AGB stars: IRAS 07399–1435 (OH 231.8+4.2), IRAS 11385–5517 (HD 101584), IRAS 14468–6004, IRAS 15405–4945, IRAS 15578–4907, IRAS 16342–3814, IRAS 17423–1755 (He 3–1475), IRAS 18491–0207 and IRAS 22036+5306

5.3.1. IRAS 07399–1435 (OH 231.8+4.2)

This well-known source is often considered to be the archetypal post-AGB star with a bipolar high-velocity mass outflow (Reipurth 1987; and references therein).

5.3.2. IRAS 11385–5517 (HD 101584)

HD 101584 belongs to a small group of stars classified optically as F- or G-type supergiants which show an excess of far-infrared radio emission. These stars were originally believed to be massive supergiants, on the basis of their optical properties, but have more recently been identified as low or intermediate mass stars in the post-AGB phase of stellar evolution.

The OH emission from HD 101584 was first discovered in this survey while high velocity CO emission was discovered by Trams et al. (1990). A detailed study of the OH maser emission from HD 101584, subsequently showed the OH masers to be located within an expanding bipolar outflow (te Lintel Hekkert et al. 1992). The detection of molecular radio emission, together with the strong far-infrared excess provides almost conclusive evidence that the star is in the post-AGB phase. The high-velocity OH outflow and dust shell characteristics of HD 101584 links these stars with IRAS sources, such as IRAS 15405–4945, which have similar radio and infrared properties but are optically invisible.

5.3.3. IRAS 14468–6004

IRAS 14468–6004 has been classified as a post-AGB star by Dong & Hu (1991) on the basis of an extremely cold circumstellar dust shell and optical emission-line features from the star. The discovery of the OH 1612-MHz maser line supports their classification of IRAS 14468–6004 as an evolved star. However, we note that it is unusual to find a “classical” 1612-MHz line profile from a post-AGB star with such a cold envelope.

5.3.4. IRAS 15405–4945

IRAS 15405–4945 has exceptionally broad OH maser emission with a velocity range of 155 km s^{-1} at 1667 MHz. A number of the OH maser features have changed significantly since the discovery of this object in 1987 (Figs. 1 and 2, te Lintel Hekkert et al. 1988). The integrated OH 1612-MHz maser intensity has nearly doubled in strength while some individual maser spikes have appeared and others have disappeared. Similar spectral changes are

Table 3. Summary of the OH emission associated with stellar sources and planetary nebulae

IRASname	LRS	$f_{60\mu m}$ [Jy]	Epoch	l [$^{\circ}$]	b [$^{\circ}$]	other names				Class.	Ref.
					OH trans.	S_{max} [Jy]	V_{max} [$km\ s^{-1}$]	$\langle V \rangle$ [$km\ s^{-1}$]	ΔV [$km\ s^{-1}$]	P	
07399 – 1435	79	$5.5E+2$	26-sep-90	231.835	4.220	OH 231.8+4.2; RAFGL 5237				PPN	5
					OH 1612 :	0.55	21.1	17.5	23.2		
					OH 1667 :	13.73	19.0	34.5	103.1	P	
11385 – 5517		$1.9E+2$	30-sep-90	293.028	5.937	SAO 239288				PPN	7
					OH 1667 :	0.66	61.0	47.5	102.4		
14468 – 6004		$5.8E+1$	29-sep-90	317.203	–0.757					PPN	9,1
					OH 1612 :	2.00	–87.9	–71.5	32.8		
15405 – 4945		$8.3E+1$	01-oct-90	329.143	3.949					PPN	4
					OH 1612 :	0.54	81.5	74.0	78.6		
					OH 1665 :	2.31	37.8	61.9	104.5		
					OH 1667 :	0.67	–15.7	62.2	155.8		
15578 – 4907		$5.8E+1$	29-sep-90	331.733	2.675					PPN	9
					OH 1612 :	0.35	–19.6	–22.6	5.9		
					OH 1667 :	1.66	–18.4	–23.2	9.7		
16280 – 4008	95	$1.2E+2$	29-sep-90	341.847	5.435	PK 341+ 5.1; NGC 6153				PN	9
					OH 1612 :	0.29	–12.3	–14.5	4.4		
16342 – 3814	05	$2.9E+2$	28-sep-90	344.074	5.847	Water-fountain-nebulae				PPN	4
					OH 1612 :	9.00	–10.2	43.8	139.6	P	
					OH 1665 :	2.86	81.3	52.9	125.6	P	
					OH 1667 :	2.22	6.1	36.6	142.1	P	
17004 – 4119		$3.7E+2$	29-sep-90	344.929	0.014	OH 344.93+0.01				OH/IR	2,5
					OH 1612 :	115.00	–21.1	–2.2	37.8		
					OH 1667 :	9.90	17.4	–2.2	39.3		
17043 – 3551		$5.5E+1$	06-jan-90	349.739	2.724					?	9
					OH 1667 :	0.28	–12.0	–15.8	7.8		
17103 – 3702	96	$8.5E+2$	28-sep-90	349.509	1.054	PK 349+ 1.1; NGC 6302				PN	8,3
					OH 1612 :	0.70	–39.9	–45.5	11.2		
					OH 1667 :	0.16	–45.7	–41.2	9.0		
17180 – 2708	94	$3.2E+1$	23-mar-91	358.536	5.471	PK 358+ 5.1				PN	9,6
					OH 1667 :	1.32	85.6	85.6			
17423 – 1755		$6.3E+1$	23-mar-91	9.364	5.779	He 3–1475				PPN	6
					OH 1667 :	1.32	81.6	52.7	57.7		
18491 – 0207	39	$1.3E+2$	16-oct-90	31.129	–1.019					PPN	6
					OH 1667 :	1.35	63.1	77.1	153.2		
19437 + 2410		$2.0E+2$	05-jan-90	60.574	–0.186					?	9
					OH 1665 :	0.78	1.7	1.7			
20272 + 3535	39	$3.5E+1$	16-jan-90	75.266	–1.841	OH 75.3–1.8				OH/IR	5
					OH 1612 :	6.60	–15.0	–3.6	22.9		
					OH 1667 :	1.24	8.8	–3.5	24.6		
22036 + 5306	36	$1.1E+2$	05-jan-90	99.634	–1.836	SAO 34043				PPN	6
					OH 1612 :	0.83	–66.9	–43.2	60.1		
					OH 1665 :	0.20	–24.6	–42.7	36.2		
					OH 1667 :	0.63	–68.1	–41.7	63.0		

References:

1. Dong & Hu 1991; 2. Fix & Mutel 1984; 3. Payne, Philipps & Terzian 1988. 4. te Lintel Hekkert et al. 1988; 5. te Lintel Hekkert et al. 1989; 6. te Lintel Hekkert 1991; 7. te Lintel Hekkert, Chapman & Zijlstra 1992; 8. Zijlstra et al. 1989; 9. this paper.

also apparent in the 1665- and 1667-MHz profiles. In particular, the OH 1667-MHz feature between -20 and $-10\ km\ s^{-1}$ has decreased in strength while the broader emission at higher velocities has increased in intensity. Te Lintel Hekkert et al. (1988) have argued that the extreme blue-shifted feature in IRAS 15405–4945 shows amplification of the background stellar emission. If this is the case, then the decrease in intensity of the blue-shifted emission may reflect changes in the stellar luminosity.

5.3.5. IRAS 15578–4907

Our classification of IRAS 15578–4907 as a post-AGB source, based on the detection of OH maser emission at 1612 and 1667 MHz, and the far-infrared colours, is uncertain. However, we note that the OH 1667-MHz emission is stronger than the OH 1612-MHz emission, which is characteristic of other post-AGB sources.

5.3.6. IRAS 16342–3814

The OH spectra of IRAS 16342–3814 have similar characteristics to IRAS 15405–4945 with a velocity range above 125 km s^{-1} at 1612, 1665 and 1667 MHz. This source also shows variability in the OH maser emission (see Figs. 3 and 4, te Lintel Hekkert et al. 1988). While the OH 1612-MHz emission was at a similar strength in 1987 and 1990, the OH main-line emission increased significantly in intensity between the two epochs. One difference between this source and IRAS 15405–4945 is that the OH maser emission is strongly circularly polarized in all lines. Circular polarization at 1612 MHz has been associated previously with massive M-type supergiant stars such as VX Sgr and VY Cma (Cohen et al. 1987).

5.3.7. IRAS 17423–1755 (He 3–1475)

The OH 1667-MHz emission from this source has a broad plateau with a central feature (te Lintel Hekkert 1991). Such emission plateaus have been observed for a number of post-AGB stars, including the sources OH 231.8+4.2 and IRAS 15405–4945. Bobrowsky et al. (1995) have recently shown that He 3–1475 has a classic bipolar structure with the OH masers aligned parallel to high-velocity ($> 500 \text{ km s}^{-1}$) optical jets.

5.3.8. IRAS 18491–0207

IRAS 18491–0207 has exceptionally broad OH 1667-MHz emission (te Lintel Hekkert 1991). The spectral profile and the spatial distribution of the OH masers are remarkably similar to those of HD 101584 and show high-velocity bipolar outflow. Unfortunately, 1612- and 1665-MHz data were not obtained for this source due to strong interference.

5.3.9. IRAS 22036+5306

IRAS 22036+5306 has also shown strong evolution in the spectral profiles between 1988 (te Lintel Hekkert 1991) and 1990. At both 1612 and 1667 MHz the low-velocity features, between -80 and -60 km s^{-1} , have increased in intensity while the high-velocity maser features, between -25 and -10 km s^{-1} , have weakened. At the same time, a plateau of emission has emerged at 1667 MHz. In 1990, the OH 1667-MHz spectral profiles of this source was very similar to the high outflow sources OH 231.8+4.2 and IRAS 15405–4945. Unfortunately, no polarization information is available. The changes of the line profiles indicate rapid evolution in the circumstellar dust shell, as discussed below.

5.4. A spectral classification scheme for evolved stars

In most cases, the OH maser spectra of post-AGB stars are characterized by large velocity widths ($\geq 30 \text{ km s}^{-1}$), stronger emission in the OH main-lines than at 1612 MHz,

and a high degree of circular polarization. The circular polarization is likely to be caused by Zeeman splitting of the spectral lines in the stellar magnetic field, indicating magnetic field strengths, at the radii of the OH masers, of at least several mG. In addition, with the exception of the planetary nebula NGC 6302 (IRAS 17103–3702), all sources for which we have multiple epochs show variability in their profile shapes and intensities.

In Table 4 we introduce a classification scheme for the evolved stars and planetary nebulae, based on the OH profile shapes. In this table the “Class A” sources have the classical OH/IR maser profile, with two emission peaks separated by $< 30 \text{ km s}^{-1}$ and weaker emission towards the stellar velocity. Class A profiles are almost always observed in the OH 1612-MHz spectra of OH/IR stars. “Class B” maser profiles show a number of individual maser features across the spectra. These may be grouped either in one velocity range (e.g. the OH 1612-MHz profile of IRAS 15405–4945), or in two roughly symmetrical velocity ranges centred on the stellar velocity (e.g. IRAS 11385–5517 and IRAS 18491–0207). “Class C” profiles consist of a plateau of emission with an additional broad ($10\text{--}15 \text{ km s}^{-1}$) emission peak. The OH 1667 MHz profiles of IRAS 15405–4945 and OH 231.8+4.2 are typical examples of this category.

6. Discussion and conclusions

6.1. The far-infrared colours of evolved stars

Figure 2 shows the number of detected and observed sources as a function of $f_{60 \mu\text{m}}$. The OH detection rate for sources with $f_{60 \mu\text{m}} > 1,000 \text{ Jy}$ is over 60 per cent (19 detections out of 30 sources), somewhat higher than the detection rate of 50 per cent obtained by te Lintel Hekkert (1991) in a similar survey of northern sources. The higher detection rate in the present survey is primarily due to the inclusion of sources with warmer IRAS colours.

Fig. 2. Number of observed IRAS sources (solid line), detections (dotted line) and detected stellar sources (long dashed line) as function of $f_{60 \mu\text{m}}$

Table 4. OH properties of the observed evolved stars

IRASname	Evolution Class. OH trans.	Stellar Type ΔV	System Pol.	Geometry Var.	OH Class
07399 – 1435	PPN (?)	MIII	Binary	Bipolar	
	OH 1612	23.2	Not Pol.		Class B
	OH 1667	103.1	Pol.		Class C
11385 – 5517	PPN	F1ap	Binary (?)	Bipolar	
	OH 1667	102.4	Not Pol.		Class B
14468 – 6004	PPN				
	OH 1612	32.8	Not Pol.		Class A
15405 – 4945	PPN			Bipolar	
	OH 1612	78.6	Not Pol.	Variable	Class Bv
	OH 1665	104.5	Pol.	Variable	Class Bpv
	OH 1667	155.8	Pol.	Variable	Class Cpv
15578 – 4907	PPN				
	OH 1612	5.9	Not Pol.		Class B
	OH 1667	9.7	Not Pol.		Class B
16280 – 4008	PN			Bipolar	
	OH 1612	4.4	Not Pol.		Class B
16342 – 3814	PPN	AI		Bipolar	
	OH 1612	139.6	Pol.	Variable	Class Bpv
	OH 1665	125.6	Pol.	Variable	Class Bpv
	OH 1667	142.1	Pol.	Variable	Class Cpv
17004 – 4119	OH/IR				
	OH 1612	37.8	Not Pol.	Variable	Class A
	OH 1667	39.3	Not Pol.	Variable	Class A
17103 – 3702	PN			Bipolar	
	OH 1612	11.2	Not Pol.		Class B
	OH 1667	9.0	Not Pol.		Class B
17180 – 2708	PN			Bipolar	
	OH 1667	3.0	Not Pol.		Class B
17423 – 1755	PPN	AI		Bipolar	
	OH 1667	57.7	Not. Pol.	Variable	Class Cv
18491 – 0207	PPN			Bipolar	
	OH 1667	153.2	Pol.	Variable	Class B
20272 + 3535	OH/IR				
	OH 1612	22.9			Class A
	OH 1667	24.6			Class A
22036 + 5306	PPN			Bipolar	
	OH 1612	60.1		Variable	Class A-Bv
	OH 1665	36.2		Variable	Class Bv
	OH 1667	63.0		Variable	Class Cv

Figures 3 and 4 show the number of detected and observed sources as a function of $r_{21} = \log(f_{25\ \mu\text{m}}/f_{12\ \mu\text{m}})$. The detection rate does not seem to be a function of r_{21} , although the stellar sources have, relatively, redded colours than the HII regions, which is also evident from Fig. 4.

Figure 5 shows a far-infrared colour-colour diagram using the IRAS flux densities at 12, 25 and 60 μm . The parameters r_{21} and r_{32} are defined as $r_{21} = \log(f_{25\ \mu\text{m}}/f_{12\ \mu\text{m}})$, $r_{32} = \log(f_{60\ \mu\text{m}}/f_{25\ \mu\text{m}})$. The parameter r_{21} clearly separates the post-AGB stars from stars on the AGB (Van der Veen & Habing 1990; te Lintel Hekkert et al. 1991). Figure 5 shows that eight of the nine post-AGB objects and all three planetary nebulae have ex-

remely cool r_{21} colours, with $r_{21} > 0.5$. For comparison, OH/IR stars on the AGB generally have r_{21} values in the range $(-0.4, 0.45)$, while optically visible Mira variables, with lower mass-loss rates than OH/IR stars have r_{21} values in the range $(-0.4, 0.0)$ (Van der Veen & Habing 1990; te Lintel Hekkert et al. 1991; Chapman et al. 1995). Note that the two stars, identified in the survey as OH/IR stars, have infrared colours at the limit of this range, indicating that they may be close to leaving the AGB.

The parameter r_{32} provides a less clear separation with considerable overlap between the values observed for Miras, OH/IR stars and post-AGB stars. The approximate r_{32} colour ranges for Mira variables and OH/IR stars are $(-1.2, -0.3)$, and $(-0.9, 0.3)$ respectively. For the

Fig. 3. Number of observed IRAS sources (solid line), detections (broken line) and detected stellar sources (long dashed line) as function of $r21 = \log(f_{25 \mu\text{m}}/f_{12 \mu\text{m}})$

Fig. 4. Number of detected IRAS sources (solid line), HII regions (broken line) and stellar sources (PPN, PN and OH/IR stars) (dotted line) as function of $r21 = \log(f_{25 \mu\text{m}}/f_{12 \mu\text{m}})$

post-AGB stars, the range of $r32$ for sources in the present survey and for other known sources (te Lintel Hekkert et al. 1992) is $(-0.6, 0.6)$.

6.2. The variability of the OH maser emission in post-AGB objects

As described in Sect. 5, the OH maser spectra of post-AGB stars observed at multiple epochs reveal strong variability in their intensities and spectral profiles. Spectral features have been observed to appear or disappear between observations separated by several years. Particularly striking are the OH variations observed for the source IRAS 22036+5306. The 1988 OH 1612-MHz spectrum of te Lintel Hekkert (1991) has a Class A profile, while the 1990 data given here show that the two OH 1612-MHz peaks have broadened to $\sim 10 \text{ km s}^{-1}$ with an increase in emission between the peaks. During this interval the OH 1667-MHz spectrum changed from a Class A to a Class C profile. The OH 1665-MHz emission was not detected in 1988 but had a Class B profile in 1990.

Fig. 5. IRAS colour-colour diagram ($r21 = \log(f_{25 \mu\text{m}}/f_{12 \mu\text{m}})$; $r32 = \log(f_{60 \mu\text{m}}/f_{25 \mu\text{m}})$): HII regions (dots), proto-planetary nebulae (open stars), planetary nebulae (filled squares), OH/IR (open triangles) and unclassified (open squares)

We now consider possible causes of the maser variations. Such spectral variations are not observed from OH/IR stars which have strongest OH maser emission at 1612 MHz. The OH 1612-MHz masers in OH/IR stars are strongly saturated and show intensity variations which follow the stellar pulsation cycle (e.g. Chapman et al. 1995). Profile variations are observed in the OH main-line maser emission from some Mira variables. These sources may also have erratic OH variability (on time scales of months), indicating partially saturated masers. Repeated imaging observations of Mira variables have shown the positions of the OH masers to be stable on time scales of at least several years (Chapman et al. 1991).

For the post-AGB stars, we suggest that the strong variability observed in the OH masers, may be caused by variations occurring in a region where a hot stellar wind interacts with the circumstellar dust shell. Such variations may be linked to strong morphological changes which occur in the circumstellar envelopes of at least some post-AGB stars (Balick 1987). One explanation for the axisymmetric geometries of the envelopes of post-AGB stars comes from hydrodynamic models for an interaction between the remnant circumstellar envelope, with a hot stellar wind (e.g. Balick et al. 1987; Mellema 1995). In these models the hot stellar winds sweep up and shock the envelopes and expand furthest in the directions of least density. Another possibility, which may be responsible for bipolarity in at least some sources, is the transfer of mass in a binary system (Waelkens 1995 and references therein). The fraction of post-AGB stars in binary systems is not known. Finally, a third mechanism which may influence

the source dynamics and geometries is the channelling of circumstellar material by the stellar magnetic fields.

Changes to the interaction zone between a hot stellar wind and a cool circumstellar dust shell might be caused by stellar pulsations, by nova-like events on the surface of the star, or by the influence of a binary companion. However, stellar pulsations are believed to be weak during the post-AGB and so would not be expected to cause strong maser variability. We therefore speculate that the maser changes are related either to nova-like events or to binary interactions.

A further, even more speculative possibility, is that the maser changes could occur if the masers behave ballistically. Te Lintel Hekkert et al. (1992) and Bobrowsky et al. (1995) have shown that for the two sources, IRAS 11385–5517 and He 3–1475, there is a strong correlation between the maser spot velocities and their projected distances from the central stars. One explanation for this is a ballistic model in which “shrapnel” is ejected from the central source with a range of expansion velocities during a single nova-like event. However, so far, no direct evidence has been obtained for nova-like events in post-AGB stars.

To distinguish between these various possibilities and to understand better the evolutionary processes occurring during the post-AGB, requires detailed observational studies. Long-term monitoring at optical, infrared and radio wavelengths is clearly needed to study the rapid and fascinating changes which occur in these stars.

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Fig. 1. OH line profiles of the detected sources

Fig. 1. continued

Fig. 1. continued

Fig. 1. continued

Fig. 1. continued

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