OH/IR STARS AND OTHER IRAS POINT SOURCES AS PROGENITORS OF PLANETARY NEBULAE

H.J. Habing, P. te Lintel Hekkert, W.E.C.J. van der Veen
Sterrewacht
Postbus 9513.
2300 RA Leiden,
THE NETHERLANDS

ABSTRACT

We briefly review the history of the search for progenitors of planetary nebulae starting with Shklovsky's (1956) paper. The inner structure of AGB stars (the likely progenitors) is sketched. The (l,b) distributions and the (l,V) distributions (V is the centre of mass radial velocity) of OH/IR stars and of planetary nebulae are compared; it is concluded that, grosso modo, both types of objects belong to the same galactic population and that most OH/IR stars develop ultimately into planetary nebulae. From a comparison of the properties of OH/IR stars and of Mira variables it is concluded that both are AGB stars with the OH/IR stars having developed from Mira variables. Most OH/IR stars are long period variables but the few that are not are probably transition cases -no longer AGB stars and very early planetary nebulae. It is argued that the IRAS catalog contains a large number of AGB stars without (detected) OH maser emission, but otherwise similar to OH/IR stars. An evolutionary sequence is presented from Mira's to oxygen-rich planetary nebulae. Some speculations are added on the formation of carbon stars and carbon-rich planetary nebulae.

1. INTRODUCTION

1.1. Some history

In the early fifties the theory of stellar evolution led to the insight that a red giant contains a very dense and compact helium core surrounded by a huge envelope of low density hydrogen. Hoyle and Schwarzschild (1955) calculated the ascent of such stars on the red giant branch and concluded that roughly half of the mass of 1.1 to 1.2$M_\odot$ is contained inside this core, the rest is outside in an envelope of much larger diameter and much lower density. Suppose that one takes a planetary nebula, and shrinks it until the volume of nebular gas has a radius of that of a red giant atmosphere, would one

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not obtain a red giant- or, in other words, is a planetary nebula a blown up red giant? This question appears to have been posed for the first time, and answered positively by Shklovskii (1956) after he had analyzed in detail the structure of several planetary nebulae. Apparently the point at issue had a wide appeal although it immediately led to another question: what causes the expansion of the stellar envelope? Ten years after Shklovskii, and not knowing the answer to this second question Abell and Goldreich (1966) in an influential paper reconfirmed Shklovskii's conclusion via several other arguments. The first of those, and one of the most powerful, had been phrased earlier by others, e.g. Osterbrock (1964) and Minkowski (1965): the galactic distribution of planetary nebula indicates that they belong to the old disk population and that they must be the result of the evolution of low-mass stars of typically, $1.2M_{\odot}$; most likely the planetary nebula stage follows that of the red giant.

Here rose, for a short time, a new problem: the red giant branch ends with a helium flash and the emerging stars become horizontal branch stars in a short while. Where do the planetary nebulae fit in? Adequate answers were almost immediately available: in 1967 at the Tatranska Lomnica Symposium on Planetary Nebulae (IAU Symposium 34) Rose (1968) and Paczynski and Ziolkowski (1968) discussed the existence of a second giant branch, later to be called the Asymptotic Giant Branch or AGB, during which energy is produced in two shells around a degenerate carbon-oxygen core: planetary nebulae emerge from AGB stars.

There thus remains the questions by what forces and in what form the AGB star ejects its envelope. The question "why there is ejection" is still not answered, but the answer to the question "how ejection takes place" has gradually been formulated over the last 15 years on the basis of, especially, infrared, millimeter and centimeter radio observations. A convenient starting point to describe this history is the publication of the Caltech 2.2µm survey of Neugebauer and Leighton (1969). This survey showed first of all that red giants, and especially long period variables, have an infrared excess indicative of a circumstellar shell. Subsequent microwave line measurements (especially of OH) showed that the outflow velocity was of the order of 15km/s and that the mass loss rate often exceeded $10^{-7} M_{\odot}/yr$. Of even more significance was the discovery of optically obscured stars with still larger mass loss rates (up to $10^{-4} M_{\odot}/yr$) -examples are two of the very first objects published from the 2.2µm survey: NML Cyg and NML Tau (Neugebauer et al., 1965). In 1968 Wilson and Barrett measured strong 1612 MHz OH maser emission from many of the "IRC objects" and this discovery was followed by the realisation by two groups of radio astronomers (in Australia and in Sweden) that similar maser sources could be detected in significant numbers by blind, unbiased 1612 MHz radio line surveys in the galactic plane. After the radio positions of maser sources had been determined with sufficient accuracy each maser source could be identified with an optically invisible infrared point source, and so the concept of an "OH/IR star" was born (Schultz et al., 1976; Evans and Beckwith, 1977). Parallel to, but independent from this radio astronomical route is the story of the (U.S.) Air

Force rocket survey; it produced the "AFGL catalogue" (Price and Walker, 1976) that contained many new infrared stars. One of the strongest was discovered independently as AFGL 2205 and, by Andersson et al. (1974), as OH26.5+0.6 -see also figure 6. Of course, most of the older surveys have been made obsolete by the IRAS full sky survey.

Detailed studies of OH/IR stars over the last 10 years have convincingly proven that the stars are Asymptotic Giant Branch stars ejecting neutral material at a low velocity (10 to 30km s^{-1}) and at a rate between $10^{-6} M_{\odot} yr^{-1}$ and a few times $10^{-4} M_{\odot} yr^{-1}$. Hence they are the missing link between red giants and planetary nebulae. In this article we review the arguments.

1.2 The inner structure of AGB stars

We summarize briefly some features of AGB stars -see figure 1. This

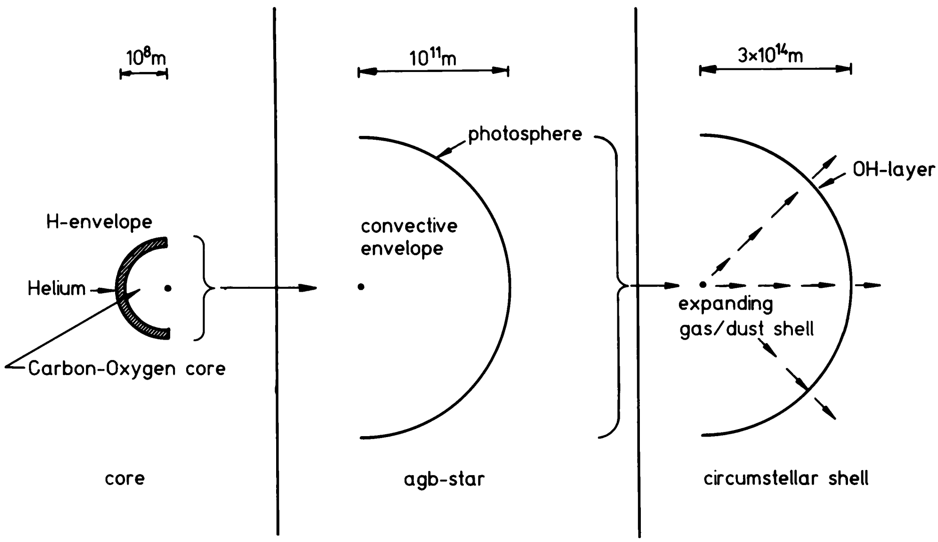

Figure 1: A schematic model for an AGB star. The core contains about 0.6 $M_{\odot}$, the envelope contains the rest.

figure is based partially on model calculations (Iben, 1971) and partially on observations. A core of oxygen and carbon with a degenerate electron gas is surrounded by a thin layer of helium, which in turn is surrounded by a large envelope of low density hydrogen: core and envelope contain comparable amounts of mass but their volumes have a ratio of 1 to 10^{6}. The envelope ends in a cool photosphere of typically 2500K. The luminosity of the star is very high (typically 6000$L_{\odot}$ but with a range from 2000 to 50,000 $L_{\odot}$); the energy is provided by the burning of hydrogen into helium at a rate dictated by the mass of the core, M_c, via the so-called Paczynski relation: $L=6x10^4$ $(M_c-0.5)$ (L and M_c in solar units). During hydrogen burning the helium layer grows in mass until it reaches a critical limit. Then the helium will quickly burn into carbon (thermal pulse) while the hydrogen burning is shut off. For a typical core of $0.6M_\odot$ such a pulse occurs once per 10^5 yr, and it lasts about 100yr (Iben and Renzini, 1983). The upper part of the envelope pulsates with a long period between 200 and 2000 days, probably because transport of the large luminosity through the outer envelope is unstable. The pulsations cause shock waves in the atmosphere, and lift up clumps of material to such heights that solid particles can form. These absorb very efficiently the photospheric photons, and acquire an outward motion; the dust particles drag the gas along and the net result is a strong, high density ($\dot{M}>10^{-7}M_\odot yr^{-1}$), slow ($\approx$15km s^{-1}) wind. Thus a circumstellar shell is formed that extends beyond $3x10^{14}$m.

2. THE STATISTICAL RELATION BETWEEN OH/IR STARS AND PLANETARY NEBULAE

2.1. Surveys, numbers and velocities of OH/IR stars

OH/IR stars are easy to pick out in a survey at 1612 MHz: they have a characteristic double peak line profile (see fig. 2). Moreover, such

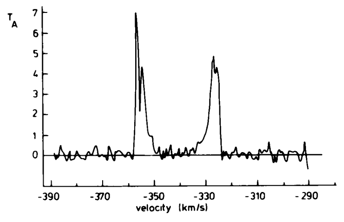

Figure 2: The 1612 MHz OH line profile of a "typical" OH/IR star. The velocity separation between the two peaks equals twice the expansion velocity of the shell; the average of the two velocities is the stellar velocity. The example line profile shown here is atypical only in that the stellar velocity is the highest known for an OH/IR star.

surveys turn up only a few (usually <5%) sources of a different kind: single peaks or complexes with several peaks; later we will come back to this point. Information derived from the double peak line profile includes the radial velocity of the star (the average of the two peak velocities) and the expansion velocity of the shell (half the difference between the two peak velocities). Several "blind" systematic OH surveys have been made: two in the southern hemisphere (Caswell and Haynes, 1975; Caswell et al., 1981) and three in the north (Johansson et al., 1977 a/b; Bowers, 1975, 1978; Baud et al. 1979a and b; 1981). In total approximately 400 sources were found. A further survey is being carried out for OH/IR stars near the galactic

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center; preliminary results have been published by Habing et al. (1983) using the Effelsberg 100m telescope and by Winnberg et al. (1985) using the VLA, which is a more efficient instrument so close to the galactic center; at present more than 60 OH/IR stars are known within one degree from the center. A catalogue of all OH/IR stars detected before the IRAS survey has been in preparation for a long time, but is now approaching completion (te Lintel Hekkert et al., 1988a). Considerable care has been taken in all surveys to carry them out in a uniform way; this facilitates reliable statistical analyses. One statistical conclusion is that the detected sources belong to the high-luminosity tail of a much wider maser-luminosity distribution: with better sensitivity one will find many more sources. The conclusion is supported by the results from the more sensitive searches near the galactic center and from the new, post-IRAS surveys.

Most of the energy produced by an OH/IR star is radiated in the infrared -typically between 2 and 60μm (see figure 6). A very profitable way to search for OH/IR stars is thus through an infrared survey. This is precisely what IRAS did and it is of no surprise that a few thousands of such infrared stars were found. Here we call stars "infrared" when they are surrounded by a dust/gas shell with an optical thickness exceeding 1.0 at 9.7μm. The few thousand are a significant fraction of all such stars in the Galaxy. Although IRAS was probably sensitive enough to detect the stars throughout the whole Galaxy, confusion limits their inclusion in the IRAS point source catalogue at low galactic latitudes, and at small longitudes. A hypothetical survey similar to that of IRAS, made with a larger telescope and thus a better angular resolution, but with the same sensitivity could possibly detect all infrared stars in the Galaxy.

The IRAS point source catalog is a treasure chest for new OH/IR stars. Two independent surveys search for 1612 MHz OH maser emission at the positions of suitably selected IRAS point sources. (1) Eder et al. (1987) used the Arecibo disk and discovered 184 new OH/IR stars in a sample of 474 IRAS sources in the sky visible to that telescope (declination between 0° and 37°). (2) te Lintel Hekkert et al. (1988b) used the Parkes 64m for a survey of the Southern Sky, including the galactic centre, and Le Squeren and others use the Nançay telescope to extend this survey to the north (see Sivagnanam and Le Squeren, 1986). The Parkes survey is now completed and the data are being reduced; about 900 new OH/IR stars have been detected. The Nançay survey has so far given about 200 new sources; a few hundred more are expected.

2.2. Galactic Distribution of OH/IR Stars and Planetary Nebulae

For each OH/IR star one measures at least four parameters: the galactic coordinates (l,b), the radial velocity of the star, V_* and the expansion velocity of the circumstellar shell, V_e. Figure 3a gives the (l,b) distribution for the stars from the Parkes, Arecibo and Nançay surveys together and figure 3b gives the (l,V_*) distribution. Figure 3a shows that the sources concentrate strongly to the galactic plane and that the large majority of the sources are in the inner Galaxy: there are only a few stars at $|l|>90°$. This is not a selection

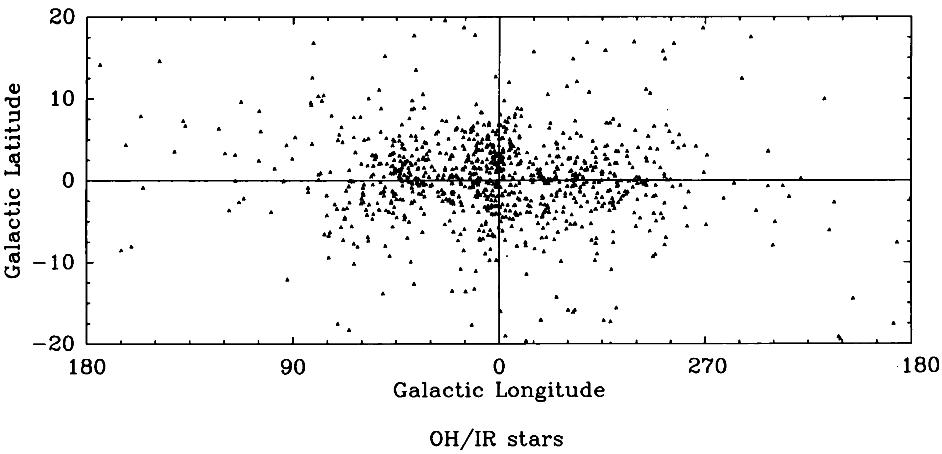

Figure 3a: (l,b) diagrams for OH/IR stars. Shown are all stars detected in the recent Arecibo and Parkes/Nançay surveys.

effect: there is a shortage of suitable IRAS sources in the Outer Galaxy. Already in the earlier, pre-IRAS surveys for OH/IR stars, especially the one by Bowers (1975, 1978), there is a shortage of stars in the anticentre. OH/IR stars are thus largely confined to galactocentric distances, $R<R_\Theta$: the Sun is close to the edge of their galactic distribution. Another feature of the pre-IRAS surveys is the strong concentration of sources toward the galactic centre; this is not so obvious in the recent IRAS based surveys. We suspect that the latter surveys have not covered completely the (confused) regions close to the galactic plane and the galactic centre. Figure 3b shows the effects of differential galactic rotation. Galactic rotation does not explain some important facts: if the stars are confined to $R<R_\Theta$ (as the l,b diagram indicates) then they will be confined to the permitted area, indicated in figure 3b, provided the stars follow closely galactic rotation. This is clearly not the case: many stars with $|l|<90°$ have velocities that deviate from galactic rotation by amounts up to 150km/s. Baud (1978; see also Baud et al., 1981) has shown that the deviations from galactic rotation are statistically correlated with the expansion velocity of the shell: larger expansion velocities imply smaller deviations from galactic rotation. The effect has been confirmed in more recent surveys (e.g. Eder et al., 1987). The explanation given by Baud also remains valid: stars with larger expansion velocities are on average more massive and thus younger;

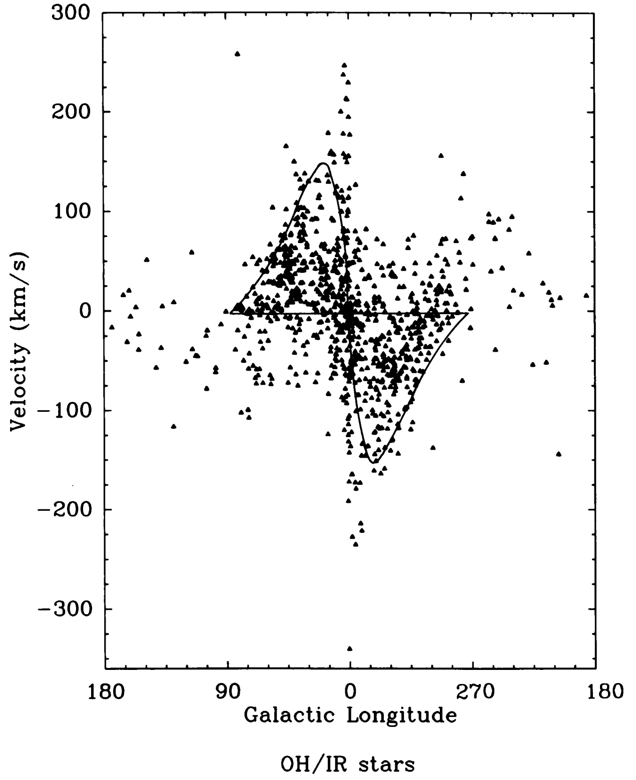

Figure 3b: (l,V_*) diagram for the OH/IR stars of figure 3a. The boundary of ruled area limits the "permitted" velocities -see the text.

thus they follow galactic rotation more closely. Comparing the average deviation from galactic rotation with that of Mira variables, Baud estimates that stars with an expansion velocity larger than the median value of 15 km/s are -on average- more massive than ≈1.2 to 1.5$M_\odot$, whereas the others are thus less massive.

As a next step compare figures 3a and 3b with similar figures for planetary nebulae (figure 4a and 4b). The shortage of planetary nebulae close to the galactic plane and to the galactic center can be explained by interstellar obscuration. The concentration of planetary nebulae toward the galactic plane seems reliable; it agrees with what is seen in figure 3a. In contrast to figure 2a, a significant number of planetary nebulae are found at $|l|>90°$. We might interpret this, however, as a relative lack of such nebulae at $|l|<90°$, because of selection effects but this interpretation we feel is not firm: are the anticentre planetary nebulae of a different kind? We conclude that figure 4a and 3a <u>may</u> represent the same distribution but real

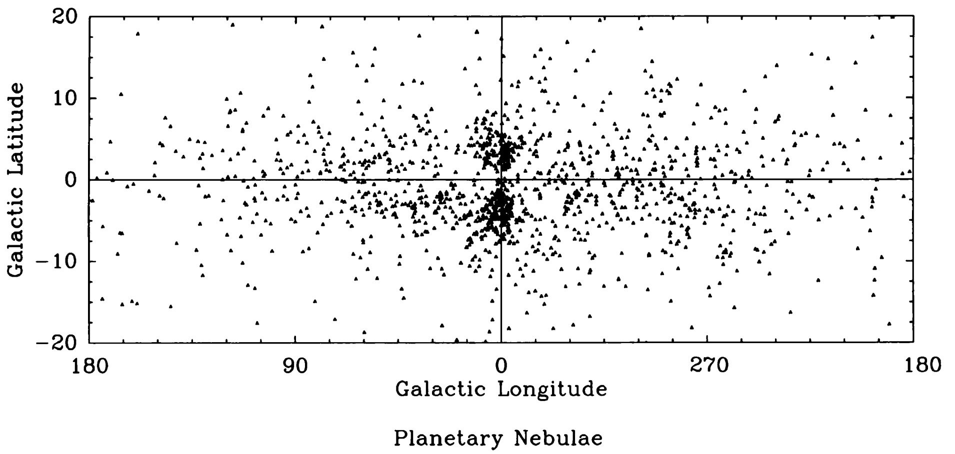

Figure 4a: (l,b) diagram for planetary nebulae. Shown are all nebulae from the list of Acker et al. 1981), plus a number of nebulae near the galactic center from data provided by A. Kalnajs (private communication).

differences may exist. A further conclusion is obtained by comparing figures 4b and 3b: these are very similar. We conclude that the agreement between the two (l,V_*) diagrams support the idea that planetary nebulae and OH/IR stars belong to the same population -and thus that the nebulae have evolved from OH/IR stars. We thus confirm Shklovskii's tentative answer (see the introduction). Selection effects in figures 4 prevent the conclusion that there is a one-to-one correspondence between OH/IR stars and planetary nebulae. It is thus possible, for example, that the most luminous OH/IR stars never become planetary nebulae or that the low-luminosity planetary nebulae discussed by Pottasch in this volume have never been OH/IR stars. However, for most objects the relation between these two kinds of objects seems well established.

Finally, there is one other argument that implies that OH/IR stars are the immediate precursors of planetary nebulae: the luminosity distribution of OH/IR stars peaks at about 6000$L_\odot$ (see further down). If we translate this into a core mass using the Paczynski relation we find a peak at about 0.6$M_\odot$. This agrees well with the observed peak in the white dwarf mass distribution (Koester and Weidemann, 1983).

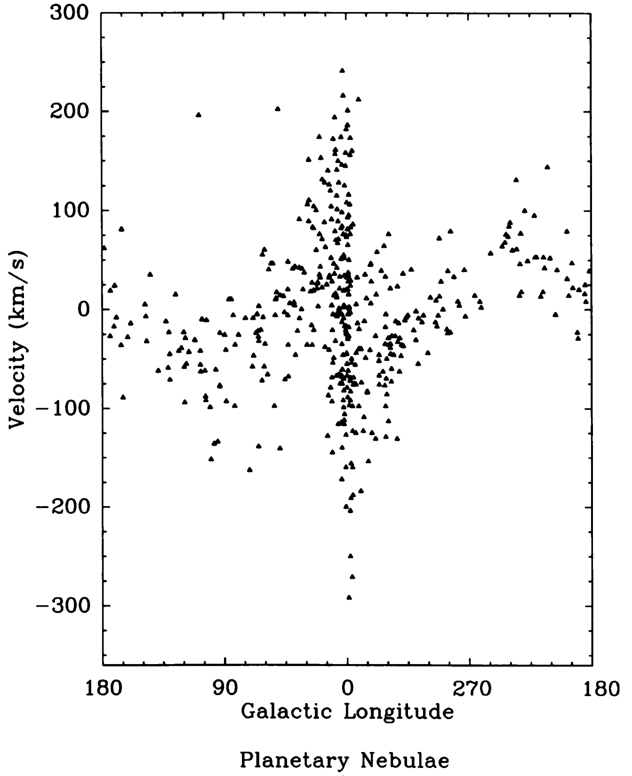

Figure 4b: (l,V_*) diagram for the planetary nebulae of figure 4a.

3. OH/IR AS AGB STARS

3.1. Luminosities, variation, mass loss and the relation to Mira variables

Having established a probable relation between OH/IR stars and planetary nebulae we now discuss the nature of the OH/IR stars. We will argue that OH/IR stars resemble in several ways a class of objects known already for a long time: the optically visible, oxygen-rich Mira variables. Our conclusion will be that OH/IR stars are AGB stars just as Mira's, but that they are equipped with some more extreme properties. In this section we discuss the luminosities, pulsation behaviour and mass loss of OH/IR stars, and we compare these properties with those of Mira's.

Luminosities

For a significant number of OH/IR stars the distance, d, has been measured. After measuring the total infrared flux F, and after correcting for interstellar extinction (symbolically written as a factor 10^A), we obtain $L=\pi d^2 F 10^A$. As we will see, the largest uncertainty is in the factor A, which cannot be derived from the observations, but for which a reasonable upper limit can be estimated. Because A=0 is a lower limit we obtain for each star a range in luminosity.

The distance to several OH/IR stars has been measured by geometrical means: by measuring first the angular diameter of the OH maser shell, and second its linear diameter. The ratio between the two gives the distance. The angular diameter (at most 2 arcsec but often less than 1 arcsec) is measured with radio interferometers -a remarkable achievement of radio astronomical techniques: the first such measurement was made with the British MERLIN array (Booth et al., 1981), followed immediately by a VLA measurement (Baud, 1981). At present some 30 stars have been mapped. The linear diameter is measured by a subtle light-travel time effect: in variable OH/IR stars the maser line strength varies quite regularly (see below); however, there is a small phase difference of the order of 0.01 between the "lightcurve" of the blue peak with respect to that of the red peak in the OH line profile. This phase difference, expressed in seconds of time, and multiplied by the velocity of light gives the diameter of the OH shell. The effect was predicted by Schultz et al. (1978) and first demonstrated by Jewell et al. (1980). The effect has been measured in a number of OH/IR stars by Herman (1983, see also Herman and Habing, 1985). For a total of 14 OH/IR stars Herman et al. (1986) derived thus a "geometrical" distance d; they found the total stellar flux, F, from groundbased and IRAS observations, and estimated A_V from a, we think, quite reasonable model distribution for extinction in our Galaxy (de Jong, 1986). The resulting luminosities are shown in Table 1. Notice the large spread! In our opinion the values of A_V so estimated should be considered as upper limits: the fact that precisely these OH/IR stars show up in the IRAS catalog (whereas others do not), probably means that in these directions the Galaxy is more transparant than the rather global model predicts. We thus give also luminosities for $A_V=0$. Table 1 shows that the more distant stars from Herman's bright star sample have luminosities exceeding the permitted limit of 56,000 $L_\odot$ (corresponding to a core mass of $1.4M_\odot$, the Chandrasekhar limit); ignoring interstellar extinction brings them all except one back to below this limit. The exception is OH 127.9-0.0 with a distance of 7 kpc in the direction of the outer galaxy -a quite peculiar situation; we are convinced that in this case the distance determination has to be checked even more carefully than in the other cases. The relatively large number of very luminous sources is a selection effect; the original sample was extracted from one of the earlier surveys in the 1612MHz OH line, in which only the most luminous sources were discovered. Therefore the luminosities are not representative.

table 1

Distances and luminosities of OH/IR stars
(adapted from Herman et al., 1986)

name	distance (kpc)	luminosity[1)] ($L_\odot$)	luminosity[2)] ($L_\odot$)
OH16.1-0.3	0.55	530	480
OH20.7+0.1	8.3	112,000	25,000
OH21.5+0.5	11.6	151,000	52,000
OH26.6+0.6	1.0	8,500	8,200
OH30.1-0.7	1.8	5,500	4,700
OH30.1-0.2	1.1	1,500	1,500
OH30.7+0.4	7.7	99,000	44,000
OH32.0-0.5	9.3	69,000	29,000
OH32.8-0.3	8.0	128,000	47,000
OH39.7+1.5	1.2	17,000	17,000
OH44.8-2.3	2.4	26,000	26,000
OH127.9-0.0	7.0	263,000	200,000

1) corrected for extinction
2) without correction for extinction

A more representative luminosity distribution has been derived by Habing (1988): he made counts of IRAS point sources with colours similar to OH/IR stars. From the (l,b) distribution of the sources he derived their spatial distribution and their luminosity distribution. The only length scale that enters this derivation is the distance of the Sun to the galactic centre (8.5 kpc). The luminosity distribution peaks at $6000L_\odot$; $16,000L_\odot$ is an upper limit.

Comparing these results with what is known for Mira variables we find a good agreement: their average luminosity is about $5000L_\odot$, only a small number have luminosities between 10,000 and 20,000 $L_\odot$.

Variability

Most OH/IR stars vary in time, both in the maser line and in the infrared. The infrared flux of 17 OH/IR stars has been monitored for a period of four years by Engels (1982; see also Engels et al., 1983). OH fluxes have been monitored in a program in Leiden started in 1980 by Herman and still being continued, now by Steeman and Habing. First results for 48 OH/IR stars and for 11 Mira variables have been published by Herman (1983); see also Herman and Habing (1985). There is good agreement between Herman's radio and Engels' infrared "light" curves -discrepancies occurred only for those lightcurves where the period exceeded the duration of the monitor program. The variation is periodic and the periods are very long (500 to 2000 days). The amplitude is large: up to 2 magnitudes bolometric. In pulsational properties the OH/IR stars are an extension of the Mira variables: amplitudes and periods are extensions toward values longer than are found for Miras, that have periods from 200 to 500 days, and bolometric amplitudes of at most 1 magnitude.

An interesting, but small group of OH/IR stars are those that do not vary at all, or vary irregularly and with a small amplitude. There are two different classes: (i) Supergiants and (ii) so-called "non-variable OH/IR stars". The first class consist of only a few stars (NML Cyg, VYC Ma and PZ Cas) with luminosities well above the AGB limit -and thus with a non-degenerate carbon-oxygen core. The second group will be discussed below in more detail.

Mass loss

The mass loss rate of OH/IR stars and of Mira's can be estimated in various ways. We will discuss the three most important methods together with their uncertainties. For a given OH/IR star these different ways lead to results that are in agreement within a factor of 2 - 5; however, in some cases discrepancies up to a factor of 100 can be found. For the Mira's a better agreement is reached usually. When mass loss rates are compared we see that the OH/IR stars are an extension to larg values larger than for Miras.

(1) Infrared mass loss rates:
One estimates the total circumstellar dust mass from the overall infrared spectrum. The weak points are the determination of the inner radius of the dust mass (or of the average density in the shell) and the gas-to-dust ratio which has to be assumed to find the total mass loss rate.

(2) OH mass loss rates:
The OH-line flux increases strongly with increasing $\dot{M}$ ($L_{OH} \sim \dot{M}^2$, Baud and Habing, 1983); this empirical fact can be used to estimate $\dot{M}$. The uncertainties involved here are the ratio $n(OH)/n(H_2)$ and the number of OH molecules necessary to get a saturated maser.

(3) CO mass loss rates:
This method is well established for Mira variables with relatively small mass loss rates, it has only very recently been used for OH/IR stars. For Mira stars the antenna temperature of the CO line is proportional to $\dot{M}$. Uncertain assumptions are in the ratio $n(CO)/n(H_2)$ and in the translation of the antenna temperature into a number of CO molecules. An unexpected problem is that the equations valid for Mira stars when used for OH/IR stars indicate mass loss rates systematically and significantly lower than those based on infrared and OH data (Omont, Forveille, Habing and Van der Veen, priv. comm.). This problem is now being studied in more detail.

Weighing in all uncertainties for the OH/IR stars the existence of mass loss rates ranging from a few times 10^{-6} to a few times 10^{-4} $M_{\odot}$/yr seems certain.

3.2. The IRAS-two colour diagram for OH/IR stars and Miras; a first scenario

From the discussions above it is concluded that OH/IR stars are related to Mira variables, and are probably also AGB stars. The two

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types are not the same: their luminosities agree, but the pulsational properties and the mass loss rates are more extreme for the OH/IR stars. This implies that OH/IR stars are "extreme Miras", and that they may have evolved from them. The suggestion finds further support in figure 5, a two-colour diagram constructed with IRAS data of OH/IR

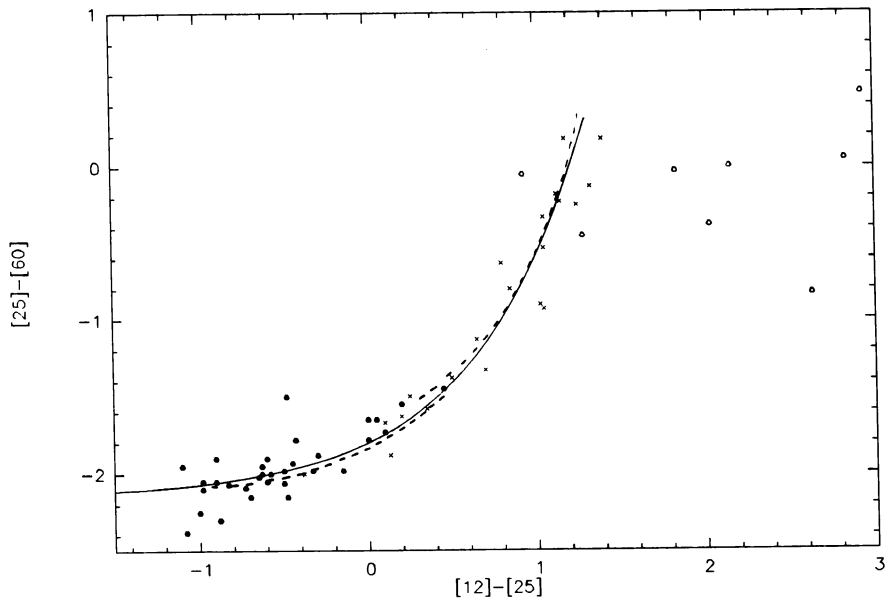

Figure 5: Two colour-diagram of (some) Mira variables and OH/IR stars constructed from IRAS 12, 25 and 60μm measurements. The Mira variables are indicated by filled circles; the variable OH/IR stars by crosses and the non-variable OH/IR stars by open circles.

stars and Miras; in its original form it was published by Olnon et al. (1983). A rather narrow sequence is defined by the Miras and the variable OH/IR stars. The non-variable OH/IR stars show deviating colours; they will be discussed later. As shown by Bedijn (1986, 1987) and by Rowan-Robinson et al. (1986) such a sequence can be interpreted as one of circumstellar dust shell models with increasing optical depth around a star of given luminosity L. The optical depth increases towards redder colours. The form and the position of the curve depend only slightly on the dust properties and not at all on the luminosity. The curve can be interpreted as one of increasing mass loss rate, where the stellar luminosity is a scaling factor at a given point on the curve.

How to interprete the curve of figure 4? A star may "start" as a Mira, stay at a fixed position in figure 4, until it switches over to become an OH/IR star, staying now at another fixed position: this viewpoint has been taken by Wood et al. (1983). Alternatively one may visualize a gradual evolution along the curve, because the mass loss rate increases continuously (Baud and Habing, 1983). Van der Veen has argued recently in favour of this latter interpretation because he observes that there is no correlation between the luminosity of a star and its position on the curve, a thing that one would expect under the first interpretation. From a count of the numbers of Miras and OH/IR stars along the curve Van der Veen concludes that the time left over on the AGB (that is: at any position the time required to reach the top of the curve) is proportional to $\dot{M}^{\alpha}$ where $\alpha \approx \frac{4}{3}$ (van der Veen, 1987).

The non-variable OH/IR stars do not fit on the theoretical curve for increasing optical depths. This fact invalidates the suggestion given by Olnon et al. (1984) that the non-variable OH/IR stars are an extension towards larger mass loss rates. A more attractive explanation has been given by Bedijn (1986, 1987): Suppose that, when a star reaches the peak of the curve, it suddenly stops to pulsate and (at the same time) to eject mass. No longer is new, warm material fed to the inside of the shell; there is only expansion. The shell cools, and in the diagram it moves to the right. Such an OH/IR star is actually no longer an AGB star, but rather a very young planetary nebula! Bedijn predicted an interesting consequence: as the shell continues to expand, its optical depth will decrease and therefore the hot remnant of the AGB star will begin to shine through the nebula at short wavelengths: non-variable OH/IR stars will have a shoulder in the spectrum at $\lambda<5\mu m$, in contrast to the variable OH/IR star where the spectrum drops at an exponential rate below $\lambda \approx 9\mu m$, see figure 6.

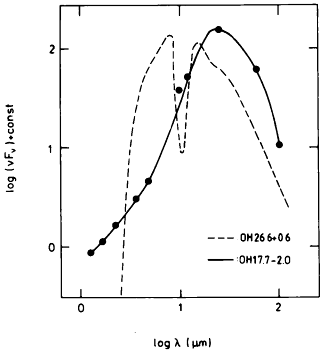

Figure 6: The infrared spectra of a variable OH/IR star (OH26.6+0.6) and of a non-variable OH/IR star (OH17.7-2.0).

This prediction has been verified in a number of cases and found to be true (van der Veen et al., 1987).

Van der Veen et al. (1987) proposed the following scenario for AGB evolution, based on the considerations given above: stars on the AGB, presumably stars with masses between 1 and 8 $M_{\odot}$, become pulsationally unstable and start to loose mass at an increasing rate; first they appear as Mira variables, later as OH/IR stars. The mass is lost at the "expense" of the envelope mass; when the envelope mass

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drops below a certain critical limit the pulsations and the mass ejection stop simultaneously and the star becomes a planetary nebula, via an intermediate stage as "non-variable OH/IR star".

In the next section we rediscuss this scenario and add (speculatively) a few new elements.

4. A LARGER SAMPLE OF DGE STARS

In a previous review we have introduced a new acronym: "DGE star" for "dust-gas envelope" stars. We will use it here again. The term was introduced to circumvent problems with two other terms: "OH/IR stars" and "CSE-stars". The term "OH/IR stars" implies that OH maser emission is detected, and this is the case in only a fraction (~1/3) of otherwise similar IRAS point sources consisting of long period variables surrounded by a dust-rich envelope. The frequently used term "CSE-star" applies also to stars with dust-free circumstellar envelopes like O and B stars -clearly a quite different category of objects.

4.1 Oxygen-rich DGE stars

In section 3 we have seen that OH/IR stars are a subsample of the point sources in the IRAS catalog that correspond to DGE stars. This allows us now to take a broader look at the evolutionary scenario developed at the end of section 3: what are the other IRAS objects, and how do they fit in? A recent analysis of this question has been made by Van der Veen and Habing (1987). Figure 7a displays all sources from the IRAS-PSC with well measured fluxes at 12,25 and 60μm ("flux quality=3" -see IRAS Explanatory Supplement). The boundaries of the diagram were chosen in such a way that less than 1% of the stellar infrared sources are not in the diagram. After consideration of (1) the association with objects from other catalogues, (2) the low resolution spectra (LRS) of IRAS and (3) the IRAS variability index, the authors divide figure 7a into several regions -see figure 7b. Most objects are in region I, II, IIIa and IV. Area I contains all objects with a blackbody spectrum with T > 2000 K longward of 6μm, as predicted by the Rayleigh-Jeans approximation. Regions II and IIIa contain stars with predominantly oxygen-rich circumstellar shells of which the ones in region IIIa show the 9.7μm feature in emission; a large number of the sources in region II and IIIa are known as Mira variables. There is a clear increase in variability of the sources going from region I via region II to region IIIa. Region IIIb contains infrared sources with the 9.7μm band in absorption, i.e. objects with a spectrum like that of OH26.5+0.6 (see figure 6); the objects are highly variable and only a few have optical counterparts. Indeed, all variable OH/IR stars are situated in region IIIb. The non-variable OH/IR stars and planetary nebulae are in region IV and V, where region V consists for about 40% of planetary nebulae. From their distribution in the sky and using a galactic model, Habing (1988) has argued that the objects in area IIIb have luminosities between 4000 and 16000 $L_\odot$

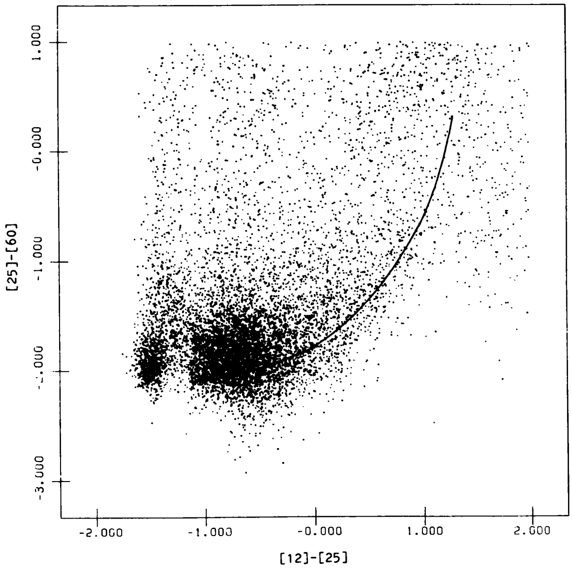

Figure 7a: Two-colour diagram of all sources in the IRAS point source catalogue, that have a "good quality" flux measurement at 12, 25 and 60µm.

with a peak at $6000L_{\odot}$; a statistical analysis of the distribution of the IRAS variability index convinced Harmount and Gilmore (1987) that more than 90% of these objects are variable with periods between 400 and 600 days. (Harmount and Gilmore analysed only stars in the galactic bulge, but we suggest that the analysis holds also outside of the bulge). In short: there are rather good indications that the objects in areas III, IV and V are similar to the OH/IR stars: the OH/IR star properties are probably representative (except for the maser emission). Thus a consideration of the point sources in II, III, IV and V lead us to the same evolutionary scenarios as proposed in section 2.

4.2 Carbon-rich DGE stars

Now turn to the other areas in figure 7b. What objects do they contain? The most interesting areas are VIa and VII: they contain large numbers of carbon stars. The objects in VIa and VII differ in some important aspects.The objects in region VIa have a very low infrared variability and the 25 to 12µm flux density ratio is that of a blackbody hotter than 1000k; however, the objects have a stronger 60µm that corresponds to such a blackbody: the indication of a cool distant circumstellar shell around a possibly very cool star. The objects in region VII have a large infrared variability and their

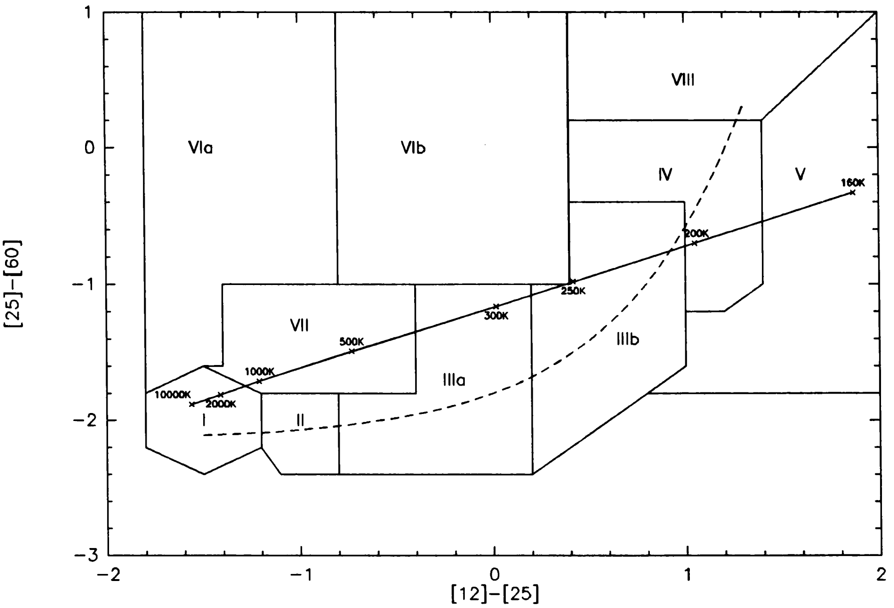

Figure 7b: The definition of the boundaries of 10 areas in the diagram of figure 6a -see text for discussion.

25μ/12μ flux density ratio is very similar to oxygen-rich Miras. The shift to larger 60μ/25μ ratio is due to the different properties of oxygen-rich and carbon-rich dust between 40 and 80μm. The circumstellar shells are carbon-rich as is evidenced by the 11.3μm emission feature in the LRS spectra (when available). Willems (1987) proposed that the stars in region VIa originate from stars with oxygen-rich circumstellar shells in region IIIa after the mass loss rate has decreased by a few orders of magnitude. Indeed in region IIIa, there is evidence for stars that have both carbon- and oxygen features. Willems (1987 see also Willems et al., 1986) and Little-Marenin (1986) found 9 carbon stars, well identified as such from optical spectra, to have the 9.7μm emission feature of oxygen-rich dust. Two of these souces were found to have H_2O maser emission as well (Benson and Little-Marenin, 1987; Nakada et al., 1987). Two others were found to have OH 1612MHz masers (te Lintel Hekkert, private comm.). Te Lintel Hekkert detected OH 1612MHz maser emission in 5 IRAS sources with the 11.3μm SiC emission feature.

This information on the simultaneous existence of oxygen-rich and carbon rich features is confusing. How to interpret this? Willems proposed, and for the moment we follow him, that we see the aftermath of the theoretically predicted third dredge-up: during a thermal pulse convection may reach in the helium/carbon burning zone and mix carbon rich material with the oxygen rich material of the envelope. If the envelope mass is small enough, which is certainly the case toward the

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end of the OH/IR phase, and the amount of carbon convectively mixed in is large enough, the carbon over oxygen rates will invert from (<1) to (>1). Te Lintel Hekkert (priv. comm.) suggests that the star can go through a phase of poor mixing with some parts of the stellar surface being oxygen-rich and others carbon-rich; the suggestion is based on the assumption that the surface of these stars is covered by a small number of adjacent, large convection cells.

The interpretation of a sudden transition should be considered as tentative. More detailed observations have to be made. But we point out an interesting aspect: if mass loss starts after the first thermal pulse (for some evidence that all Mira's have undergone a thermal pulse see, Little et al., 1987), then it is a critical question at what moment the superwind will set in -at what phase of the period between two thermal pulses? If the superwind starts and finishes just before a thermal pulse, the star may become an oxygen-rich planetary nebula; but if the last thermal pulse takes place during the superwind phase, then the mass of the envelope may be low and the deposition of carbon may turn the star into a carbon rich planetary nebulae. There is thus a certain randomness involved and a strict deterministic model of carbon star formation ("all stars of so much mass will eventually become a carbon star") may not work: becoming a carbon star may be an accident. The considerations above lead us to extend the proposed evolution scheme to that given in figure 8.

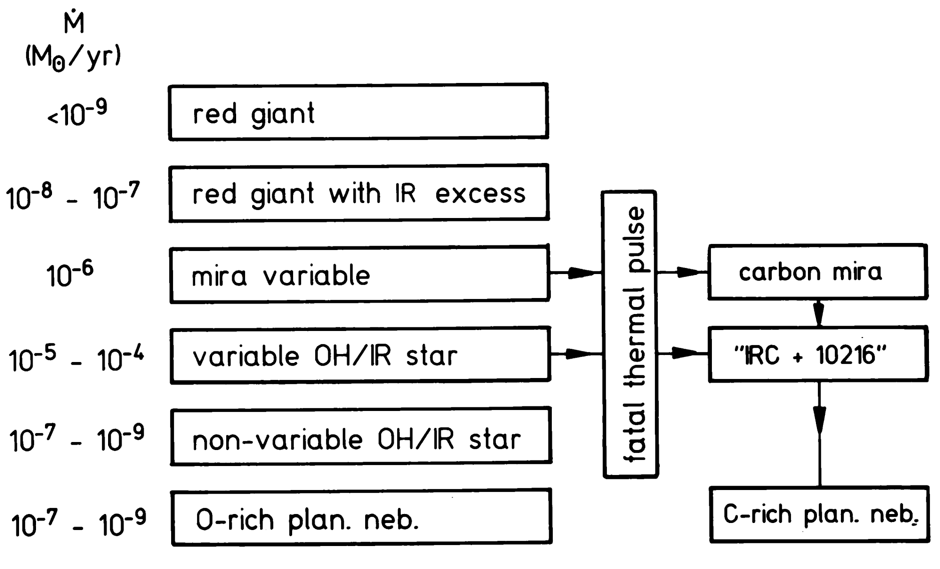

Figure 8: Evolutionary scheme as proposed in this review.

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5. THE TRANSITION OF AGB TO THE PLANETARY NEBULA STAGE

5.1 Post AGB stars and proto planetary nebulae

Above we have argued that the decay of an AGB star involves two episodes, or a "two-wind model", much as Kwok et al. (1978) predicted. We have given our views of the first episode, that of the high density, low velocity wind. What about the transition to the low density, high velocity wind? We have already concluded that some objects with non-variable OH 1612MHz emission and a non-variable infrared spectrum are probably transition objects (see the posters by Volk and Kwok and by Van der Veen et al. during this symposium). The recent discovery of 1612MHz OH maser emission in several very young planetary nebulae (see the poster by Zijlstra et al. during this symposium) confirms our conclusion: the OH maser is a good tracer for a cool, distant shell (its typical distance from the star is $3x10^{14}$m). The search for transition objects (or proto-planetary nebulae) has been a pastime during almost all previous planetary nebula symposia; no case survived. The IRAS data, coupled with our improved insight in the "first episode", make it likely that this symposium will have seen the first proto-planetaries of longer duration. Time (that is: time on a human scale) will show this.

5.2 The transition of a spherically symmetric wind into a bipolar flow

The observations of the 1612 MHz line emission from OH/IR stars give a result that on closer consideration is quite surprising: there are only a few objects known with mass loss in cones ("bipolar flows", thus: not spherically symmetric); such objects are rare. Examples of symmetric outflow are OH231.8+4.2 (for a recent paper with the references to earlier work see Reipurth, 1987), IRC+10420 (Diamond et al., 1983) and OH19.2-1.0 (J. Chapman, private communication). Most OH maser maps obtained by aperture synthesis arrays (VLA, MERLIN) show spherical symmetry. In all cases there are some discrete blobs present that contribute to a certain amount of chaos, but the overall impression is one of symmetry. This is supported by the fact that in 1612 MHz surveys almost all sources have exactly the two emission peaks; only rarely a single peak or three or more peaks are found. Te Lintel Hekkert and Caswell found 25 unusual objects among their 900 detections; Eder et al. report similar results.

The dominating presence of spherical symmetry contrasts with the predominance of other symmetries in the shapes of planetary nebulae (see the contribution by Balick in this volume). Why is there spherical symmetry during the first episode of mass loss and is this absent during the second episode?

6. FINAL QUESTION: WHAT ABOUT DOUBLE STARS?

A large fraction of main sequence stars are double or worse. In this review we have ignored multiplicity and discussed the objects as if

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they were single. Is multiplicity of importance? In our estimation multiplicity is not required to explain the observed phenomena. Again, only time wil teach us how close we are to the truth.

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