

High Latitude Supergiants

L.B.F.M. Waters¹, C. Waelkens², and N.R. Trams³

¹ SRON Laboratory for Space Research, P.O. Box 800, 9700 AV Groningen, The Netherlands

² Astronomical Institute, Catholic University Leuven, Celestijnenlaan 200B, B-3030 Heverlee, Belgium

³ ESTEC, Space Science Department, P.O. Box 299, Noordwijk, The Netherlands

Abstract

A review is given of the properties of high latitude supergiants in the context of the late stages of evolution of low mass stars. Evidence for mass loss is reviewed. The binarity of the high latitude supergiants is discussed, and the effects of binarity on the evolution and geometry of the circumstellar material. A model for the geometry of the circumstellar shells of binary post-AGB stars is proposed, which is similar to that proposed by Morris (1989) for bipolar transition objects.

1 Introduction

The distribution of stars with supergiant spectra in our Galaxy shows a strong concentration towards the Galactic plane, which is consistent with the fact that these stars are thought to be massive, luminous objects that are born in the Galactic plane. It has been noted however that not *all* supergiants are confined to the Galactic plane: some can be found at very large Galactic latitudes, which would put them at large z distances if they have the same luminosity as the supergiants found in the Galactic plane. Some of the supergiants at high z have very high space velocities, and could be run-away stars that started their life in the Galactic plane but were ejected from the plane by some process.

Another group of high latitude supergiants however distinguishes itself by several intriguing properties: (1) they sometimes are metal deficient, (2) they often show enhanced CNO surface abundances, (3) they have large space velocities consistent with them being halo objects, and (4) they have a large infrared excess due to circumstellar dust. This suggests a different origin for these objects than ejection from the Galactic plane, and it has been suggested that they are in fact low mass stars that have recently left the Asymptotic Giant Branch (AGB), and are rapidly evolving towards higher effective temperatures.

The IRAS all-sky far-IR survey has been very successful in finding such supergiants with dust shells, and the sample of stars has increased significantly in recent years. This review de-

scribes the general properties of the high latitude supergiants, and discusses their connection to the late stages of the evolution of low mass stars.

2 Selection of Candidate Post-AGB Stars

Before discussing the properties of post-AGB stars, it may be useful to define this evolutionary phase. A post-AGB star by definition has left the Asymptotic Giant Branch, i.e. has stopped losing mass at rates that are typical for AGB evolution (10^{-6} to $10^{-4} M_{\odot} \text{ yr}^{-1}$), and is moving towards the left in the HR diagram. The effective temperature of post-AGB stars is between about 5000 K and 25000 K, which is the temperature when a Planetary Nebula (PN) *may* become observable. In fact it would be more correct to call *all* stars that have left the AGB post-AGB stars, without making the distinction about the presence of a PN.

Since the evolution of stars from AGB to the PN stage is characterized by large amounts of circumstellar dust, by far the most successful way to find post-AGB stars is to look for stars with an IR excess due to (hot or cool) dust. This method has been used extensively since the results of the IRAS all-sky survey became available, and has resulted in an impressive list of new candidate post-AGB stars (e.g. Parthasarathy & Pottasch, 1986, 1988; Pottasch & Parthasarathy, 1988; Lamers et al., 1986; Waelkens et al., 1987, 1991a; van der Veen et al., 1989; García-Lario et al., 1989; Le Bertre et al., 1989; Hrivnak et al., 1988, 1989; Manchado et al., 1989a; 1989b; Trams et al., 1990; Slijkhuis et al., 1991; Trams et al., 1991; Slijkhuis, 1992; Oudmaijer et al., 1992; Zijlstra et al., 1991). Most searches in the IRAS database are concentrated in a small area in the IRAS colour-colour diagram, and are based on the assumption that post-AGB stars have infrared colours intermediate between those of AGB stars and of young PNe. In many cases such cool IRAS sources have been identified with weak optical counterparts. The cross-correlation of optical catalogues with the IRAS data has resulted in stars with various amounts of IR excess and IR colours, i.e. they are scattered in the IRAS far-IR colour-colour diagram (Oudmaijer et al., 1992). In Table 1 we list some candidate post-AGB stars with emphasis on optically bright objects. We stress that Table 1 is not complete.

The candidate post-AGB stars found this way can very roughly be divided into two groups based on their continuum energy distribution: (1) objects in which the IR luminosity is much larger than the optical luminosity, and (2) objects with comparable optical and IR luminosities. It is clear that searches for post-AGB stars using IRAS will be biased towards finding objects in the first group, while searches using cross-correlations between optical catalogues and the IRAS Point Source Catalogue will be biased towards the second group.

The difference in energy distribution of the two groups is due to large differences in the amount of circumstellar dust and its optical depth in the visual and UV, and can be understood in the context of the slowly expanding and cooling AGB remnant: objects with large AGB mass loss should on average have strong IR emission and weak optical counterparts, while stars with smaller AGB mass loss rates can have bright optical counterparts. Of course the time that has elapsed since the end of the AGB also plays an important role: old objects will be less obscured than young ones.

Table 1: Candidate post-AGB stars

star	name	sp. t.	hot dust	H α	binary	remarks
HD 44179	Red Rectangle	B9 II-III	++	strong, complex	+	visual binary
HD 46703		F I	-	weak shell	-	
HD 52961		F I	+	weak shell	?	
HD 53300		F I	-	absorption	?	
HD 56126	U Mon	F5 I	-	moderate shell	+?	RV var. 25 km s ⁻¹
HD 59693		F8 Ibe	+	strong emission	?	
HD 89353		A7 I	++	strong shell/Pcyg	+	
HD 95767		F0 Ib	+	weak shell	+	
HD 101584	HR 4049	F0 Ib	++	strong P Cygni	+?	P _{orb} = 430 d Not enough data
HD 108015		F3 Ib	+	weak shell (:)	+	
HD 112374		F3 Ia	-	weak shell	?	
HD 137569		B5 III	-	absorption	+	
HD 161796	LN Hya	F3 Ib	-	weak shell	-	P _{orb} = 530 d
HD 163506		F2 Ia	++	moderate P Cyg	+	
SAO 65424		F5 Ib	-	filled in	?	
HD 170756		F2 Ibpe	+	strong emission	+	
HD 172324	89 Her	A0 Iab	-	strong emission	?	Not enough data var. H α
HD 172481		F2 Ia	+	?	+	
HD 179821		G5 I	?	?	?	
HD 187885		F3 I	-	moderate shell	-	
HD 190390	HR 7671	F 1 III	?	shell	?	RV by pulsation
HD 213985		A2 I	++	moderate shell	+:	
BD+39 4926		A7-F0	-	absorption	+	
SAO 173329		F5 I	+	strong P Cygni	+	
SAO 239853	AC Her	A9 Iab	-	weak shell	-	Photom. per. 260 d P _{orb} = 775 d (:) Not enough data
SAO240664		F5 Ia	-	weak P Cygni?	?	
BD-62 5428		F2	+	?	+	

Data for SAO 240664 taken from Oudmaijer (private communication).

Some stars have been identified as post-AGB objects based on their surface abundance pattern. Examples are BD+39 4926 (F I) and HD 137569 (B5 III), both high latitude weak-lined objects, whose metal and CNO abundances suggest they are low mass, evolved stars that show the results of nuclear burning processes in the photosphere (Kodaira, 1973; Danziger & Jura, 1970). See however also Waelkens (these proceedings). In their search for massive, Pop. I B stars at high Galactic latitude, Conlon et al. (1991; 1992, in preparation) have found some stars with Pop. II abundances and enhanced CNO, again pointing to an evolved stage of evolution of low mass stars. Quin & Lamers (1992) find two high latitude B stars that could be low mass post-AGB stars. With only one exception all objects that were identified by Conlon et al. (1992) as post-AGB stars on the basis of their photospheric abundances, were not detected by IRAS (Conlon, private communication). This may in part be due to the fact that a significant fraction of the stars is at a large distance, but that cannot fully explain the very low IRAS detection rate. The conclusion must be that the searches for post-AGB

stars using IRAS are incomplete, and that a significant population of post-AGB stars without strong IR excess is missed. Such objects most likely will never develop an observable PN.

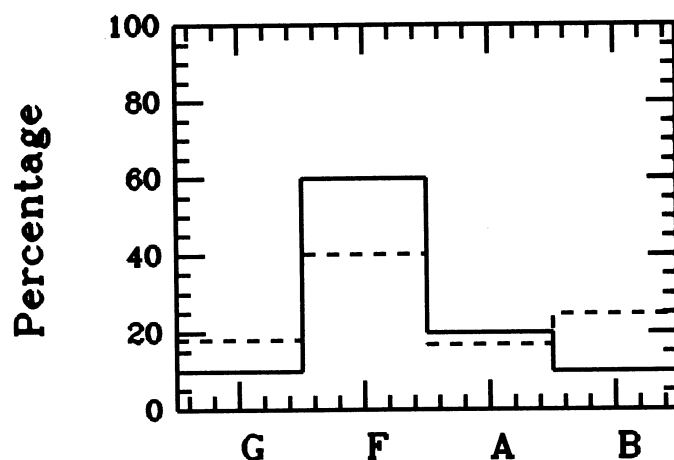


Figure 1: *The distribution of supergiants in the SAO catalogue with IR excess over spectral type (taken from Oudmaijer et al., 1992). The dashed line gives the distribution for all supergiants, the solid line that of the candidate post-AGB stars. Notice the large fraction of F stars.*

In Figure 1 we have plotted the distribution of supergiants in the SAO catalogue that show an IR excess over spectral type (dashed line), and the candidate post-AGB stars in that sample (solid line). The large number of F stars is immediately apparent, as well as the lack of A and B stars. We conclude that irrespective of the method that is used (with perhaps the exception of the B stars with pop. II abundances), only cool post-AGB stars are found: post-AGB stars with circumstellar dust on average have T_{eff} roughly between 5000 K and 7500 K. Interestingly, Slijkhuis (1992) also found mostly post-AGB stars with spectral types F or later, using the IRAS colour-colour diagram as starting point. His objects still suffer from large amounts of circumstellar extinction, and probably have much more circumstellar dust than the F stars in the sample of Oudmaijer et al. (1992). It is likely that the samples of Oudmaijer et al. (1992) and Slijkhuis (1992) have different initial mass ranges (see also below). The lack of A and B stars in the sample can be understood in the context of the evolutionary tracks of Schönberner (1979; 1983), if we assume that no significant post-AGB mass loss is present over that predicted by the Reimers (1975) law.

Oudmaijer et al. (these proceedings) have calculated the expected distribution of post-AGB stars over spectral type on the basis of the Schönberner tracks. They find that low mass post-AGB stars that evolve very slowly to higher T_{eff} spend most of their time as a B star, simply because the B spectral range comprises a large range in T_{eff} . The AGB remnant however will cool rapidly and the star will not be detected in the far-IR once it becomes a B star. More massive post-AGB stars increase their speed of evolution after they reach $T_{eff} \approx 8000$ K, and therefore spend most of their time as cool F or G type post-AGB

stars. The lack of B stars can then be understood as a combination of the rapid evolution of high mass post-AGB stars above $T_{eff} \approx 8000$ K, and the dispersion of the AGB remnant of low mass post-AGB stars before they reach spectral type B. The fact that the post-AGB stars without IR excess tend to be pop. II halo objects with spectral type B supports this interpretation. This would imply that the sample of Slijkhuis (1992) on average has higher mass progenitors than that of Oudmaijer et al. (1992), because the latter sample has much less circumstellar dust, while they have comparable spectral type ranges.

Oudmaijer et al. (these proceedings) also discuss the Galactic latitude distribution of supergiants in the SAO catalogue with IR excess detected with IRAS. They find that the distribution of B and A stars in their sample is consistent with that expected for Pop. I stars, i.e. concentrated towards the Galactic plane. The IR excess in these objects may be due to free-free emission from a strong stellar wind, but also objects with prominent dust emission are found. The F supergiants however show a much wider Galactic latitude distribution. This indicates that these stars belong to a different, low mass population.

3 Mass Loss: Past and Present

The continuum and line spectrum of the bright post-AGB stars is full of evidence for mass loss, and we summarize this evidence here.

3.1 Mass loss: past

The IR continuum energy distribution of many post-AGB stars is characterized by a large IR excess due to a cool dust component, with typical colour temperatures of the order of 100 – 200 K. The simplest explanation for the presence of this dust is that we observe the slowly expanding and cooling remnant of a previous phase of high mass loss, presumably when the star was still on the AGB. This interpretation is confirmed by the many CO and OH observations that are by now available (e.g. Likkell et al., 1987; 1991; Bachiller et al., 1988; Loup et al., 1990; Trams et al., 1990; Alcolea & Bujarrabal (1991); van der Veen et al., 1992; Bujarrabal et al., 1992), that show OH maser emission, CO (1 – 0) and CO (2 – 1) emission line profiles which are typical for detached shells, and with expansion velocities that are typical for AGB stars, i.e. 5 to 20 km s⁻¹.

There is evidence that the high latitude supergiants on average have had a lower mass loss on the AGB than typical AGB stars (e.g. Herman & Habing, 1985). This is based on the smaller amount of circumstellar dust and on estimates of the AGB mass loss rate from CO line profiles (van der Veen et al., these proceedings). Also the expansion velocity of the AGB wind as measured from the CO line profiles is lower, which points to a low initial mass.

The CO expansion velocities and the dust energy distributions can be used to derive kinematic ages for the post-AGB stars, i.e. the time since the end of the AGB can be estimated. These estimates usually give timescales of the order of 500 to a few thousand years, which again suggests the stars have only recently left the AGB.

3.2 Mass loss: present

Present-day post-AGB mass loss is an important parameter in the evolution of the star towards the PN stage. We identify three ways to observe post-AGB mass loss: (1) $H\alpha$ emission, (2) CO emission in the near-IR, and (3) continuum emission from hot dust.

3.2.1 $H\alpha$ emission

For the majority of the bright post-AGB stars we now have high resolution, high S/N $H\alpha$ spectra, and for several stars we can also study the $H\alpha$ variability. The observed line profiles can be divided into three types: (a) photospheric absorption profiles, (b) P Cygni profiles and (c) double-peaked (shell) profiles. The vast majority of the stars has some $H\alpha$ emission; examples of these profiles are plotted in Figure 2. In most cases the profiles show photospheric line wings that indicate a low surface gravity, and a central emission component. The differences in line profiles obviously reflect differences in mass loss rates and in wind structure: the stars without $H\alpha$ emission apparently have no mass loss, while the stars with $H\alpha$ emission have some ionized circumstellar gas. In the case of P Cygni profiles, the wind is probably spherically symmetric, and is accelerated to the terminal velocity within a distance of a few stellar radii (examples: 89 Her and HD 101584). These terminal velocities are of the order of 150 to 300 km s^{-1} , which is slightly higher than the escape velocity of the star if we assume a mass of $0.6 M_{\odot}$. The mass loss rates are difficult to estimate, but range from less than $10^{-8} M_{\odot}\text{yr}^{-1}$ to $10^{-6} M_{\odot}\text{yr}^{-1}$.

The shell profiles are less straightforward to interpret. The lines often have a violet emission peak that is stronger than the red one, and in some stars we see this ratio change over a period of time. The shell profiles can be explained in several ways. It is possible that the $H\alpha$ emitting gas is distributed in a flattened disk around the star. In that case one would expect a correlation between the width of the $H\alpha$ emission and the rotation of the star ($v \sin i$), which is not apparent. Also one would expect to see some stars pole-on so that the two peaks would merge into a single peak, but such profiles are not (yet) observed.

The shell profiles could also be the result of gas which is falling back onto the star. As discussed by Waelkens (these proceedings), there is evidence that at least in some stars that are in wide binary systems some material has fallen back to the star. Infall of material could explain why the violet emission peak is stronger than the red one. However in many stars that are not thought to be binaries these shell profiles are also observed, i.e. shell profiles are not restricted to binaries. The origin of the infalling material in single stars is not clear.

Shell profiles are often observed in pulsating stars, such as W Vir stars (Lèbre & Gillet, 1992) and RV Tau stars (Lèbre & Gillet, 1991). They are thought to arise when part of the material that was lifted above the photosphere by a shock wave, is falling back to the star, and a new shock wave is developing in the lower atmosphere. Photometric and radial velocity (RV) studies of bright post-AGB stars indeed show that the atmospheres are pulsating, but the amplitudes of the RV variations in these stars are only a few km s^{-1} , much smaller than the tens of km s^{-1} found in the W Vir and RV Tau stars. This could explain why the $H\alpha$ emission never is very strong (with a few notable exceptions!), and it also explains the very

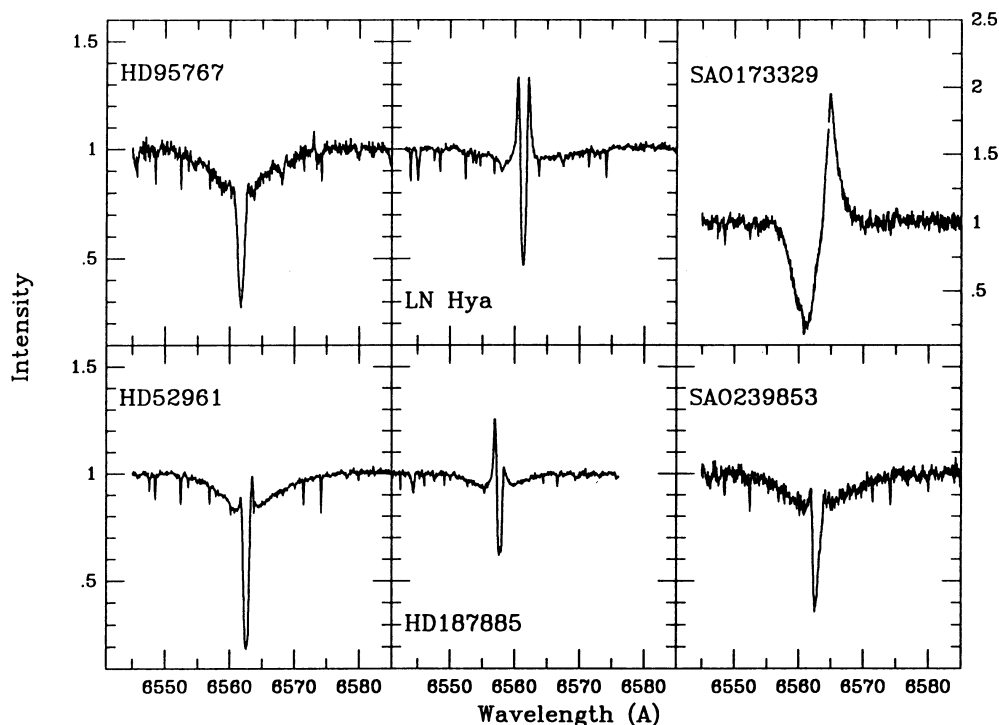


Figure 2: *High resolution $H\alpha$ line profiles of some high latitude supergiants. Notice the shell profile in LN Hya and HD 52961, and the strong P Cygni profile in SAO 173329*

presence of the ionized material: the shocks that run through the atmosphere will ionize the outer layers.

3.2.2 CO near-IR emission

The near-IR spectra of some high latitude supergiants show clear evidence for CO emission in the rotation-vibration bands at a wavelength of $2.3\ \mu\text{m}$. We show the spectra of HD 101584 and of AC Her (an RV Tau star) in Figure 3. The CO must be quite warm in order to excite these bands, and it seems likely that this occurs close to the star and not in the detached AGB remnant: the CO in the AGB remnant is observable in the rotation transition in the (sub)mm wavelength range.

The resolution of the spectra is not sufficient to determine the Doppler broadening of the emission, but we speculate that this CO is part of the material which is also observed in the $H\alpha$ emission and in the hot dust. The presence of this warm CO suggests that the UV radiation field of the star is shielded already close to the star.

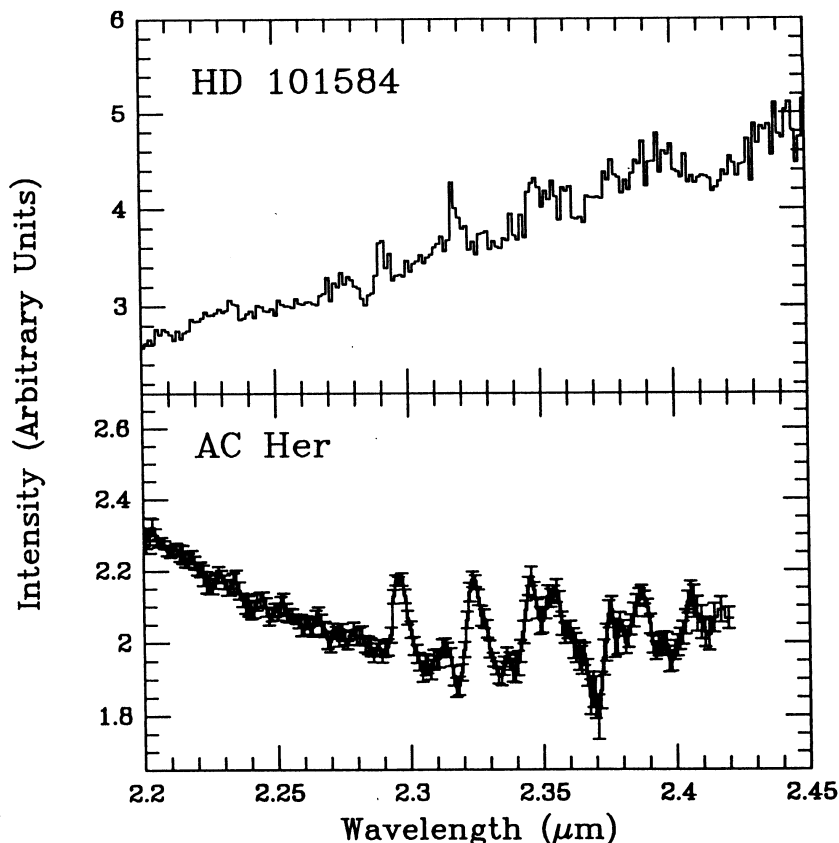


Figure 3: 2 micron spectra of the RV Tau star AC Her (taken by T.R. Geballe at UKIRT) and of HD 101584 (taken by W. van der Veen at ESO). Notice the CO emission at 2.3 μm .

3.2.3 Hot dust

The presence of hot circumstellar dust ($T_{\text{dust}} \approx 500 - 1000$ K) in some high latitude supergiants was first noted by Allen (1973) and Humphreys & Ney (1974a). The latter authors suggested that HD 101584 is in a binary system with a cool companion (Humphreys & Ney, 1974b), but the IRAS observations indicate that the IR excess is due to an extended circumstellar dust shell (Parthasarathy & Pottasch, 1986). The hot dust must be relatively close to the star if we assume that it is in thermal equilibrium with the photospheric radiation field of this star: typical distances to the inner radius of the hot dust shells are several tens to a few hundred stellar radii (Alcolea & Bujarrabal (1991); Trams et al., 1992). It was pointed out by Trams et al. (1989) that this hot dust must have been formed very recently, i.e. in a *post-AGB wind*, because it is so close to the star. In order to explain the amount of IR radiation, a mass loss rate of the order of $10^{-7} M_{\odot} \text{yr}^{-1}$ is required. Such mass loss rates are not incompatible with the mass loss estimates based on the strength of the $H\alpha$ emission, and have a significant impact on the evolution of the star: the mass loss rates are of the order of

the nuclear burning rates in the H-shell of low mass post-AGB stars. Therefore post-AGB mass loss will speed up the evolution and affect the formation of a PN.

The interpretation of the hot dust in terms of post-AGB mass loss is not as straightforward as suggested above however. We will come back to this point in Section 5.3.

4 Binarity

A significant fraction of all stars is in binary or multiple systems, and there is no reason to assume that this situation is different for the high latitude supergiants. The binary character of these stars is often difficult to establish, because the photospheres are not at rest but show evidence for pulsations or turbulent motion. The radial velocity (RV) variations due to these motions are sometimes difficult to disentangle from the binary motion, and long series of high quality observations are necessary to establish the nature of the RV variations. The combination of RV with photometric variations is quite powerful in distinguishing between pulsation and orbital motion.

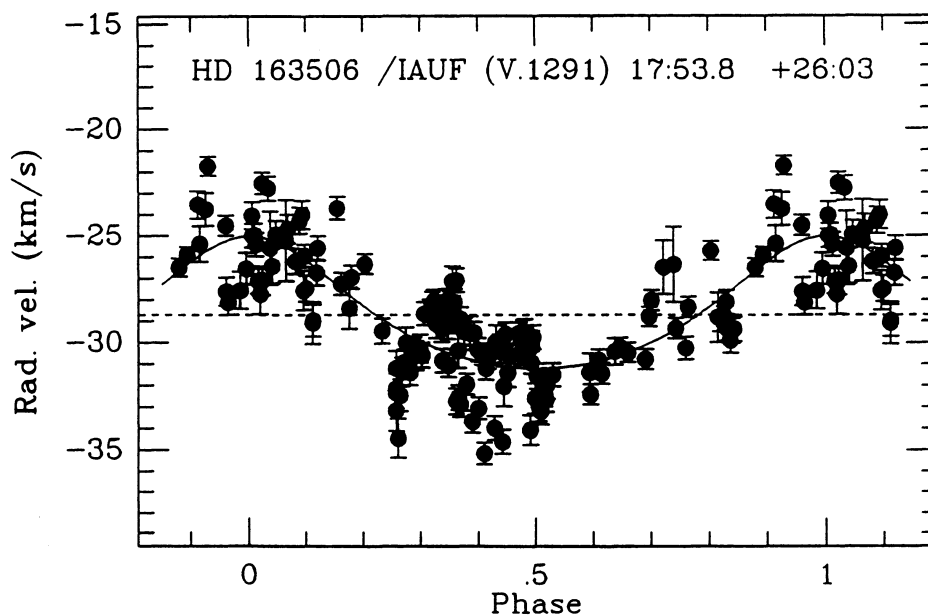


Figure 4: *Radial velocity curve of 89 Her based on CORAVEL measurements, and folded with a period of 288 days. The scatter around the mean curve is probably due to motions in the photosphere of the star.*

In Table 1 we have indicated for each star the evidence for RV variations, and the nature of these variations (pulsation, binarity). Most of the data in Table 1 on RV variations was collected by one of us (CW) using CORAVEL. When available, an orbital period is

given. As can be seen, a significant fraction of the stars in Table 1 is in a binary system. It is difficult to make any estimate about the fraction of binaries among the high latitude supergiants however, since the sample in Table 1 is strongly biased towards stars with an IR excess. As we will show below, binarity influences the presence of circumstellar dust. In Figure 4 we show the RV curve of 89 Her, taken from Waters et al. (1992). The orbital periods in Table 1 are of the order of a few hundred days, i.e. we are dealing with rather wide orbits.

Inspection of Table 1 shows that the occurrence of *hot dust* is somehow associated with the binary nature of the star. Apparently hot dust preferentially occurs in these wide binaries! There is no correlation between binarity and *cool* dust, nor with the presence or absence of H α emission. This may have implications for the interpretation of the hot dust in terms of post-AGB mass loss, because in that case one would expect to see a correlation between the strength of H α and the size of the IR excess. Such a correlation is not observed.

5 Geometry of the Circumstellar Material

There is growing evidence that in some high latitude supergiants the circumstellar material is not distributed spherically symmetrically, but is in a flattened disk around the star. This evidence is based on (i) the lack of energy balance between UV absorption and IR emission by the circumstellar dust, (ii) the lack of correlation between the strength of the H α emission and the size of the near-IR excess, (iii) the peculiar shape of the CO (1 – 0) and (2 – 1) millimetre line profiles in some stars, (iv) the apparent correlation between the presence of hot dust and the binary character, and (v) the presence of narrow emission lines of permitted transitions of neutral metals (Fe I, Cr I). There is reason to believe that the binary character of some stars is the cause for this deviation from spherical symmetry, and we propose that in binaries the material is distributed in the orbital plane in a **circum-system disk**. Not all stars that are in binary systems show all these effects, but some of this can be explained by differences in viewing angle of the system. We discuss the evidence for circum-system disks in some detail below.

5.1 Energy balance

It was noted by Trams et al. (1992) that for some post-AGB stars there is no balance between the amount of energy emitted by the dust in the IR and the UV absorption by that dust. If we assume that the circumstellar absorption has no significant grey component, the lack of energy balance implies that the dust is not distributed spherically symmetric around the star, but is in some flattened geometry viewed at an intermediate inclination angle. Examples of stars with no energy balance are 89 Her (see also Waters et al., 1992), HR 4049, HD 213985, HD 101584 and the Red Rectangle (Waelkens et al., 1992). In Figure 5 we show the observed energy distributions of 89 Her and the Red Rectangle.

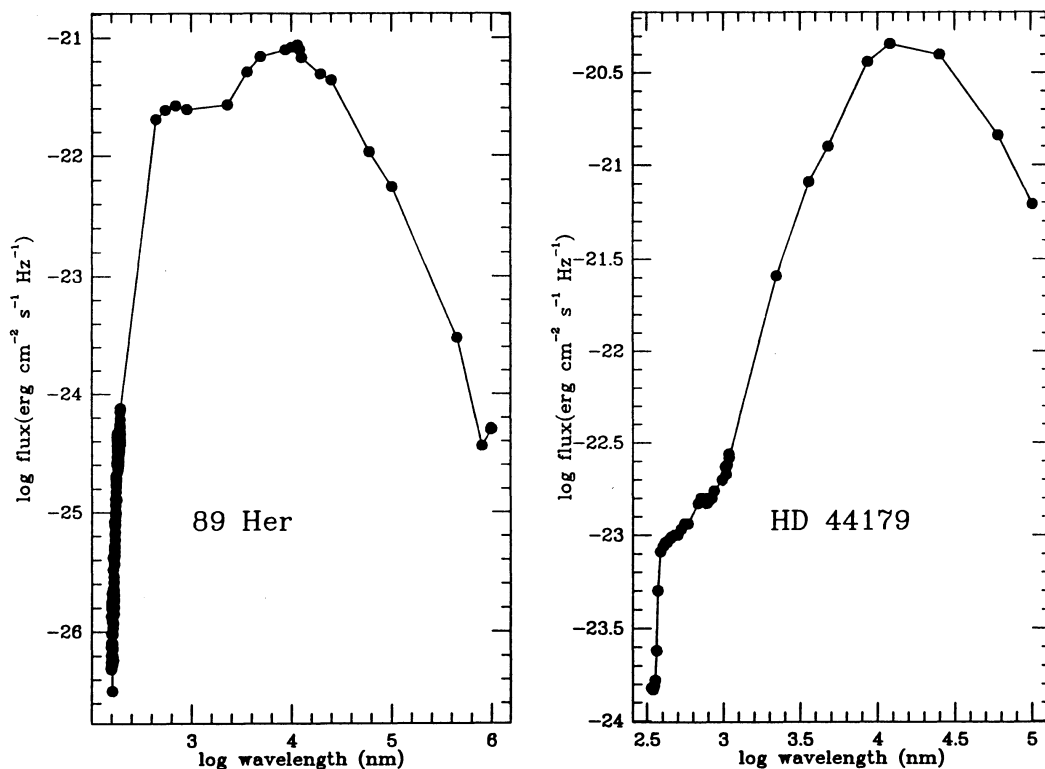


Figure 5: Observed energy distributions of 89 Herculis and HD 44179 (the Red Rectangle). Notice the large IR excess at wavelengths longwards of $1\ \mu\text{m}$, due to both hot and cold dust. In both stars there is no energy balance between the absorption in the UV and the emission in the IR.

5.2 Strength of $H\alpha$ versus near-IR excess

The presence of $H\alpha$ emission and hot dust in many post-AGB stars suggests that this hot dust is formed in the outflow which is also observed in $H\alpha$ (see e.g. Trams et al., 1989). However there is no obvious correlation between the size of the near-IR excess and the strength of $H\alpha$. A good example is HD 213985, which has a strong near-IR excess about equal in size to that of HR 4049 (Waelkens et al., 1987), but the $H\alpha$ emission of HD 213985 is much weaker than that of HR 4049 (Waters et al., 1991). Furthermore, there are indications that the $H\alpha$ emission of HD 213985 is variable, but the near-IR excess hardly varies (Whitelock et al., 1989). If the hot dust is formed in the $H\alpha$ outflow, the variations in mass loss rate should strongly affect the size and colour of the dust excess in the near-IR. This is not observed however.

A comparison of the size of the IR excess and H α emission of 89 Her and HD 101584 shows that while the mass loss rates inferred from H α differ by as much as a factor 100 (Trams et al., 1990), the V–L colour differs only by 0.6 mag, and part of this difference in colour can be attributed to interstellar extinction. The amount of *hot dust* in both stars is roughly equal, but there is a large cool dust component in HD 101584 which is not present in 89 Her.

The H α emission in 89 Her is quite weak, and has a P Cygni profile with a terminal velocity of the order of 150 – 300 km s^{–1} (Sargent & Osmer, 1969). The density in the wind is very low at the distance where the temperature in the wind has dropped sufficiently for dust to condense. It is argued by Waters et al. (1992) that dust cannot easily condense in the H α outflow of 89 Her because of these low densities, but Figure 5 demonstrates that a strong near-IR excess is present. Again this suggests that the dust is not formed in the H α outflow.

5.3 Hot dust and binarity

Table 1 shows a remarkable correlation between the presence of hot dust and the binary character of the star. This correlation was first noted by Waters et al. (1991). The data strongly suggest that when an evolved, low surface gravity star is in a (wide) binary system, a ring of relatively hot dust will form. In fact, this correlation seems to hold for a wide variety of objects in very different stages of evolution. For instance, the binary 3 Puppis (A2 Iabe) is a massive Pop I star with a low mass companion in an 140 day orbit, with a strong near-IR excess. Other objects that show hot dust are ν Sgr and KS Per, both interacting binaries with a helium star and a hot companion (e.g. Drilling & Schönberner, 1982). In view of the energy balance arguments discussed above, it is tempting to conclude that the hot dust is in a disk around the system. The presence of hot dust does not seem to correlate with the strength or shape of the H α emission.

The origin of the hot dust is not clear. It could have accumulated during a phase of high mass loss (presumably the AGB), or it could have been deposited during Roche lobe overflow. We cannot exclude the possibility that the dust was accumulated over a long period of time with a low mass loss rate, but we consider this a less likely scenario. It is important to realize, however, that in the case of circum-system disks the temperature of the dust does not give information on the time that has elapsed since it was ejected by the star: the dust presumably is in a Keplerian disk whose temperature is determined by the dimensions of the system and the T_{eff} of the central star.

We recall here that the accumulation of dust in a binary system of which one component is an AGB star has been suggested in the case of the carbon stars with oxygen-rich dust envelopes (Willems & de Jong, 1986; Little-Marinin, 1986; Morris, 1987, 1989; Lloyd-Evans, 1990; Lambert et al., 1990). The binary character was investigated recently by Barnbaum et al. (1991) who demonstrate that the RV variations in several objects suggest they are in wide binary systems. Perhaps the O-rich dust was accumulated in a circum-system disk while the AGB star was still O-rich, and this AGB star has since evolved to the C-star phase. It is not impossible that these C-stars with O-rich envelopes that are in binary systems eventually evolve into the peculiar post-AGB stars with circum-system dust rings.

5.4 Narrow emission lines of neutral metals

The optical spectrum of 89 Her and HD 101584 is characterized by numerous narrow emission lines of neutral metals such as Fe I and Cr I. In the case of 89 Her these emission lines are variable in strength, and have a constant radial velocity which is equal to the systemic velocity (Climenhaga et al., 1987). In HD 101584 it is not known whether these emission lines vary in radial velocity. Since the lines are in emission, it is likely that they are formed in the circumstellar shell, and the constant RV suggests that in the case of 89 Her the lines are formed in a shell which is around the system. Recent high-resolution observations of the spectrum around $H\alpha$ show similar emission lines in HD 108015 and HD 95767, which are also binaries.

5.5 A model for the circumstellar material in binaries

The arguments presented above lead to a model for the geometry of the circumstellar material in which several components can be identified. In Figure 6 we sketch the geometry of the model, which is in fact the model of Waters et al. (1992) for the 89 Her system. This geometry is very similar to the geometry of bipolar transition objects proposed by Morris (1989).

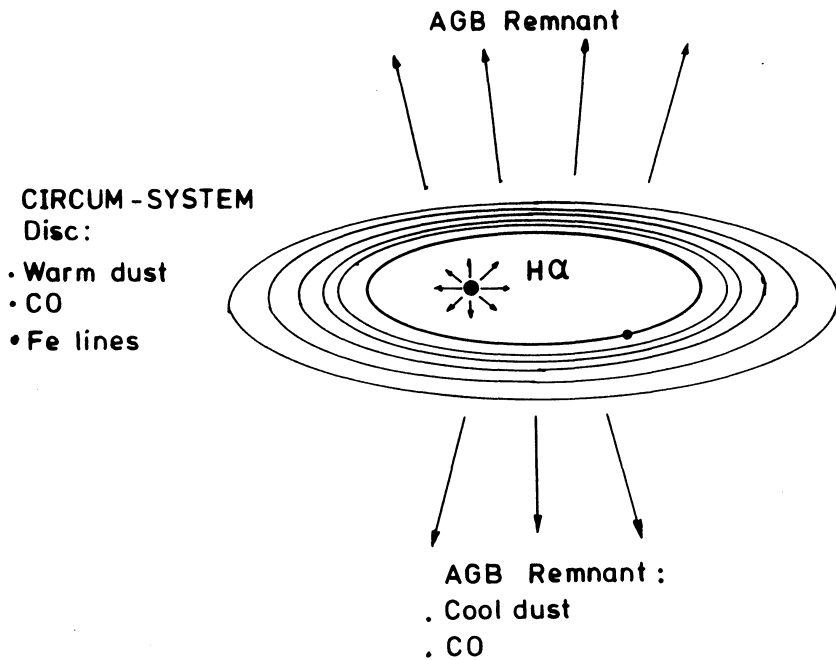


Figure 6: Geometry of the circumstellar material in binary post-AGB stars. Notice the similarity to the model proposed by Morris (1989) for bipolar transition objects

The model consists of a central star which is evolved (possibly a post-AGB star) and a companion in a wide, sometimes eccentric orbit. The nature of the companion is not clear: the mass functions that are observed suggest in some cases that the mass of the two stars is roughly equal. If we assume that the central object is a post-AGB star, its mass is of the order of $0.6 M_{\odot}$, and hence the companion is also of this mass. The companion could therefore be a white dwarf or a low mass main sequence star. Orbital periods are of the order of a few hundred days. The system as a whole is surrounded by a ring of gas (both atomic and molecular) and dust. The temperature of the dust in the ring is determined by the dimension of the system, the effective temperature of the central star, and the absorption properties of the grains, and will in most cases be quite warm: 500 to 1000 K. The central star is losing mass via a stellar wind, and this wind runs into the ring of gas and dust in the orbital plane. This may cause the narrow emission lines that are seen in stars as 89 Her and HD 101584. Such a model can qualitatively explain many of the observed properties of some high latitude supergiants. We stress however that the binary model most likely does not apply to *all* stars in Table 1. Objects as HD 161796 can be explained very well in the context of a single low mass post-AGB star.

As mentioned above many stars also have a strong far-IR dust component. This cool dust component most likely is the AGB remnant, and we can incorporate this in the binary model if we assume that in directions perpendicular to the orbital plane the AGB wind could flow freely, while it was partly stored in a disk in the orbital plane.

Direct imaging of many transition objects in the optical, near-IR and (sub)-mm, as well as the very shapes of PNe suggest that strong deviations from spherical symmetry must occur at some point in the late stages of AGB evolution, and that non-sphericity is very common. The models developed by Morris (1989) for bipolar nebulae and in this paper for the high latitude supergiants use binarity to produce the asymmetric envelope. One may wonder whether binarity can be invoked to explain *all* bipolar nebulae, or that other mechanisms could also produce deviations from spherical symmetry. It is interesting to note that in the pulsation driven wind models by Bowen & Willson (1991) the mass loss rate depends strongly on the surface gravity. This suggests that a relatively small variation in gravity over the surface of a star could result in non-spherical mass loss. Perhaps rotation could provide such a change of gravity going from pole to equator.

6 Effects of Binarity on Evolution

For orbital periods smaller than a few years it is likely that at some point during the evolution the binary nature will influence the further evolution of the system, because the increase in radius of the primary of the system will result in its filling the Roche lobe, and mass transfer will take place. The effects of Roche lobe overflow on the further evolution of the system are not clear. It is possible that the orbit shrinks due to the drag the companion experiences, and perhaps the stars will form a common envelope system in which the two stars coalesce.

Eggleton (1989) discusses different evolutionary scenarios for low mass close binaries with orbital periods between about 100 and 1000 days. He concludes that under the assumption of

conservative evolution the system must pass through a common envelope phase, accompanied by spiral-in. This scenario can explain the binary central stars of PNe with very short orbital periods.

A different evolution may occur if a substantial amount of mass is lost from the system before Roche lobe overflow (RLOF) begins. Mass loss via a stellar wind could result in a reversal of the mass ratio before RLOF, and in that case the mass transfer need not be catastrophic (Eggleton, 1989), and the system could perhaps survive as a wide binary. If the binaries listed in Table 1 are indeed post-AGB stars, the latter scenario is more likely in view of the orbital elements. It is, however, not clear how in these scenarios the orbits can remain eccentric.

The orbital elements found by Waelkens et al. (1991b) for HR 4049 and by Waters et al. (1992) for 89 Her suggest that these stars did not fit in their Roche lobe when they were on the AGB, even assuming very low luminosities at the tip of the AGB. One may wonder whether or not these stars were on the AGB at all. In this context it is interesting to note that Luck et al. (1990) report a deficiency of s-process elements in 89 Her, which is difficult to understand if the star has recently left the AGB. Fernie & Sasselov (1989) note that three well studied UU Her stars, among which 89 Her, show no evidence for an increase in T_{eff} over a period of several tens of years. Such an increase in T_{eff} is expected if the stars are on a rapid evolution to the PN stage. Zsoldos & Sasselov (1992) argue that the UU Her stars are not low mass post-AGB stars, but are a population of more massive supergiants at high Galactic latitude.

It is clear that the class of high latitude supergiants is composed of different components: 'genuine' single post-AGB stars (such as HD 161796), and more complex objects in binary systems (such as HR 4049 or 89 Her), that may or may not have passed through an AGB phase. In order to establish the nature of individual objects, a detailed multi-frequency study is necessary.

Acknowledgements

We thank Wil van der Veen and Tom Geballe for the use of their CO near-IR spectra, and René Oudmaijer for providing Figure 1. Hans van Winckel is acknowledged for assistance with the H α profiles. We thank Heny Lamers, Eric Bakker, René Oudmaijer and Hans van Winckel for many interesting discussions.

References

- Alcolea, J., Bujarrabal, V.: 1991, *A&A* **245**, 499
- Allen, D.A.: 1973, *MNRAS* **161**, 145
- Bachiller, R., Gómez-González, J., Bujarrabal, V., Martín-Pintado, J.: 1988, *A&A* **196**, L5

- Barnbaum, C., Morris, M., Likkell, L., Kastner, J.H.: 1991, *A&A* **251**, 79
- Bowen, G.H., Willson, L.A.: 1991, *ApJ* **375**, L53
- Bujarrabal, V., Alcolea, J., Planesas, P.: 1992, *A&A* **257**, 701
- Climenhaga, J.L., Smolinski, J., Krempec-Krygier, J., Krygier, B., Krawczyk, S.: 1987, in *Circumstellar Matter*, IAU Symp. 122, eds. I. Appenzeller & C. Jordan, p. 329
- Conlon, E.S., Dufton, P.L., Keenan, F.P., McCausland, R.J.H.: 1991, *MNRAS* **248**, 820
- Danziger, I.J., Jura, M.A.: 1970, *ApJ* **161**, 997
- Drilling, J.S., Schönberner, D.: 1982, *A&A* **113**, L22
- Eggleton, P.P.: 1989, in *From Mira's to Planetary Nebulae: Which Path for Stellar Evolution?*, eds. M.O. Mennessier and A. Omont, Editions Frontieres, p 513
- Fernie, J.D., Sassellov, D.D.: 1989 *PASP* **101**, 513
- García-Lario, P., Manchado, A., Pottasch, S.R., Suso, J., Olling, R.: 1989, in *From Mira's to Planetary Nebulae: Which Path for Stellar Evolution?*, eds. M.O. Mennessier and A. Omont, Editions Frontieres, p 474
- Herman, J., Habing, H.J.: 1985, in *Physics Reports*, Vol 124, no. 4, p. 255
- Hrivnak, B.J., Kwok, S., Volk, K.M.: 1988, *ApJ* **331**, 832
- Hrivnak, B.J., Kwok, S., Volk, K.M.: 1989, *ApJ* **346**, 265
- Humphreys, R.M., Ney, E.P.: 1974a, *ApJ* **187**, L75
- Humphreys, R.M., Ney, E.P.: 1974b, *ApJ* **190**, 339
- Kodaira, K.: 1973, *A&A* **22**, 273
- Kwok, S., Hrivnak, B.J., Boreiko, R.T.: 1987, *ApJ* **312**, 303
- Lambert, D.L., Hinkle, K.H., Smith, V.V.: 1990, *AJ* **99**, 1612
- Lamers, H.J.G.L.M., Waters, L.B.F.M., Garmany, C.D., Pérez, M.R., Waelkens, C.: 1986, *A&A* **154**, L20
- Le Bertre, T., Epchtein, N., Gouiffes, C., Heydari-Malayeri, M., Perrier, C.: 1989, in *From Mira's to Planetary Nebulae: Which Path for Stellar Evolution?*, eds. M.O. Mennessier and A. Omont, Editions Frontieres, p 477
- Lèbre, A., Gillet, D.: 1991, *A&A* **246**, 490
- Lèbre, A., Gillet, D.: 1992, *A&A* **255**, 221
- Likkell, L., Omont, A., Morris, M., Forveille, T.: 1987, *A&A* **173**, L11

- Likkel, L., Forveille, T., Omont, A., Morris, M.: 1991, *A&A* **246**, 153
- Little-Marenin, I.R.: 1986, *ApJ* **307**, L15
- Lloyd-Evans, T.: 1990, *MNRAS* **243**, 336
- Loup, C., Forveille, T., Nyman, L.Å, Omont, A.: 1990, *A&A* **227**, L29
- Luck, R.E., Bond, H.E., Lambert, D.L.: 1990, *ApJ* **357**, 188
- Manchado, A., García-Lario, P., Pottasch, S.R.: 1989a, *A&A* **218**, 267
- Manchado, A., García-Lario, P., Pottasch, S.R.: 1989b, *A&AS* **156**, 57
- Morris, M.: 1987, *PASP* **99**, 1115
- Morris, M.; 1989, in *From Mira's to Planetary Nebulae: Which Path for Stellar Evolution?*, eds. M.O. Mennessier and A. Omont, Editions Frontieres, p 520
- Oudmaijer, R.D., van der Veen, W.E.C.J., Waters, L.B.F.M., Trams, N.R., Waelkens, C., Engelsman, E.: 1992, *A&AS* (in the press)
- Parthasarathy, M., Pottasch, S.R.: 1986, *A&A* **154**, L16
- Parthasarathy, M., Pottasch, S.R.: 1988, *A&A* **203**, 117
- Pottasch, S.R., Parthasarathy, M.: 1988, *A&A* **192**, 182
- Quin, D.A., Lamers, H.J.G.L.M.: 1992, *A&A* (in the press)
- Reimers, D.: 1975, in *Problems in Stellar Atmospheres and Envelopes*, eds. B. Baschek, W.H. Kegel and G. Traving, Springer Verlag Berlin, p 229
- Sargent, W.L.W., Osmer, P.S.: 1969, in *Mass Loss from Stars*, ed. M. Hack, p 57
- Schönberner, D.: 1979, *A&A* **79**, 108
- Schönberner, D.: 1983, *ApJ* **272**, 708
- Slijkhuis, S., Hu, J.Y., de Jong, T.: 1991, *A&A* **248**, 547
- Slijkhuis, S.: 1992, Thesis, University of Amsterdam
- Trams, N.R., Waters, L.B.F.M., Waelkens, C., Lamers, H.J.G.L.M., van der Veen, W.E.C.J.: 1989, *A&A* **218**, L1
- Trams, N.R., van der Veen, W.E.C.J., Waelkens, C., Waters, L.B.F.M., Lamers, H.J.G.L.M.: 1990, *A&A* **233**, 153
- Trams, N.R., Waters, L.B.F.M., Lamers, H.J.G.L.M., Waelkens, C., Geballe, T.R., Thé, P.S.: 1991, *A&AS* **87**, 361
- Trams, N.R., Waters, L.B.F.M., Waelkens, C., Lamers, H.J.G.L.M.: 1992, *A&A* (submitted)

- van der Veen, W.E.C.J., Habing, H.J., Geballe, T.R.: 1989, *A&A* **226**, 108
- van der Veen, W.E.C.J., Trams, N.R., Waters, L.B.F.M.: 1992, *A&A* (submitted)
- Waelkens, C., Waters, L.B.F.M., Cassatella, A., Le Bertre, T., Lamers, H.J.G.L.M.: 1987, *A&A* **181**, L5
- Waelkens, C., van Winckel, H., Bogaert, E., Trams, N.R.: 1991a, *A&A* **251**, 495
- Waelkens, C., Lamers, H.J.G.L.M., Waters, L.B.F.M., Rufener, F., Trams, N.R., Le Bertre, T., Ferlet, R., Vidal-Madjar, A.: 1991b, *A&A* **242**, 433
- Waelkens, C., van Winckel, H., Trams, N.R., Waters, L.B.F.M.: 1992, *A&A* **256**, L15
- Waters, L.B.F.M., Trams, N.R., Waelkens, C.: 1991, in *The Infrared Spectral Region of Stars*, eds. C. Jaschek and Y. Andrillat, Cambridge University Press, p 40
- Waters, L.B.F.M., Waelkens, C., Mayor, M., Trams, N.R.: 1992, *A&A* (submitted)
- Whitelock, P.A., Menzies, J.W., Catchpole, R.M., Feast, M.W., Carter, B.S., Marang, F., Roberts, G., Sekiguchi, K.: 1989, *MNRAS* **241**, 393
- Willems, F.J., de Jong, T.: 1986, *ApJ* **309**, L39
- Zijlstra, A.A., Gaylard, M.J., te Lintel Hekkert, P., Menzies, J., Nyman, L.Å, Schwarz, H.E.: 1991, *A&A* **243**, L9
- Zsoldos, E., Sasselov, D.D.: 1992, *A&A* **256**, 107