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POST-AGB STARS

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■ **Abstract** In this contribution, a review is presented on the ample data obtained on post-AGB stars, both on the central stars and their circumstellar material. The fast evolutionary phase is characterized by a rapid change in the properties of the objects, but the variety is so large that there is yet no clear consensus on how the detailed studies of individual objects are linked together by evolutionary channels. The absence of strong molecular veiling in the photospheres of the central stars, together with a spread in intrinsic metallicity make post-AGB stars very useful in constraining AGB chemical evolutionary models. We discuss the surprisingly wide variety of chemical signatures observed. The onset in the creation process of the panoply of structures and shapes observed in planetary nebulae occurs during the short post-AGB evolution, but the physical nature of the processes involved is still badly understood. In the rapidly growing field of circumstellar mineralogy, post-AGB stars have their story to tell and also the molecular envelope changes significantly due to dilution and hardening of the stellar radiation. The real-time evolution of some objects suffering a late thermal flash is reviewed and their possible link to other hydrogen-deficient objects is discussed. Any review on stellar evolution has a section on binaries and this contribution is no exception because binaries make up a significant fraction of the post-AGB stars known to date.

1. SETTING THE STAGE

Post-AGB stars are luminous objects of low and intermediate initial mass ($M_* \leq$ 8–9 $M_\odot$) in a final stage of evolution: they ended their Asymptotic Giant Branch (AGB) evolution by a phase of very strong mass loss (10^{-7}–10^{-4} $M_\odot$ yr^{-1}), evolve on a fast track to hotter effective temperatures at roughly constant luminosity but are not yet hot enough to ionize the circumstellar material and to emerge as a Planetary Nebula (PN) prior to cool down as a white dwarf (WD).

Post-AGB stars cover a wide range of effective temperatures between extreme AGB stars just after the superwind [e.g., nonvariable OH/IR stars, Habing et al. (1987)], to objects like AFGL618, which are on the verge of inonizing the circumstellar matter. Especially the resolved objects are often dubbed protoplanetary nebulae (PPN), but in this review the more universal name "post-AGB star" is used.

Figure 1 illustrates an important characteristic of post-AGB stars: the very broad spectral range of their electromagnetic emission allowing observational studies using a wide range of techniques and wavelengths. When the optical depth in the line of sight is not too large, UV and optical fluxes allow the (chemical) study of the central star; the circumstellar opacity characteristics and in some cases, also the electronic transitions of circumstellar molecules. Moreover, it is clear that infrared (IR) observations of the thermal radiation of circumstellar dust are key ingredients in the study of these objects. It is no surprise that the all-sky survey of IRAS was fundamental in discovering and studying the properties of post-AGB objects. The bulk of the circumstellar material is, however, in the gas phase with typical dust/gas mass fractions of $\sim$1%, and this molecular envelope is best traced by (sub)mm and radio line emission. Recently, the spectroscopic capabilities of the Infrared Space Observatory (ISO) proved to be an ideal tool to study the chemical and physical properties of the circumstellar environment. In addition, the high spatial resolution imaging, mainly of the *Hubble Space Telescope* (*HST*), but also from the ground, resolved the geometry of the circumstellar material of many objects, despite their relative large distances.

As transition objects, the post-AGB stars are often discussed both in conferences of Planetary Nebulae (PNe) and of AGB stars. The latest issues are *IAU Symp. 191* from the symposium held in 1998 in Montpellier, France (*The Asymptotic Giant Stars*, edited by A. Lèbre, T. Le Bertre, and C. Waelkens) and *IAU Symp. 209* from the symposium held in 2001 in Canberra, Australia (*Planetary Nebulae—Their Role and Evolution in the Universe*, edited by S. Kwok, M. Dopita, R. Sutherland). In 2000, between these two symposiums, a workshop was held in Torun, Poland, focusing on *Post-AGB Objects as a Phase of Stellar Evolution* (edited by R. Szczerba and S.K. Gòrny).

The scope of this contribution is not to give a historical review on post-AGB research [see Kwok (1993) in this series] but to focus on recent observational and theoretical results together with ample references to the literature. The omnipresent "and references therein" will be omitted. Because the AGB evolutionary phase determines many observational characteristics of post-AGB stars, we start with the theoretical framework on (chemical) AGB and post-AGB evolution on which we base the interpretation of the observational data. Of course in the iterative process, the latter is constraining and guiding the first.

Section 3 covers the different approaches of searching for the rare post-AGB objects, all of which are biased in some sense. In the next sections we cover the different components of a post-AGB object: the central star (Section 4) and the circumstellar envelope (Section 5). The central stars tell the whole story of initial composition modulated by dredge-up processes and the focus is on the surprisingly wide variety of chemical composition we detect. I only touch upon the morphology of the circumstellar envelope, and the subsection is kept extremely short compared with the scientific and aesthetic value since it was masterly reviewed in last year's issue by Balick & Frank (2002). The focus is more on the physical-chemical composition and evolution of the circumstellar dusty shell both in C- and O-rich environments. Section 6 covers the objects that are evolving so fast that we can observe nonfatal stellar evolution in real time. Binarity and more importantly the impact of binarity on our view on post-AGB stellar evolution is detailed in Section 7. We end with a glance in the crystal ball to foretell a bright future for post-AGB research.

2. THEORETICAL CONSIDERATIONS

During the late AGB evolution, two fundamental processes determine the ultimate fate of the object: driven by large scale stellar pulsations, a strong external dusty mass loss is developed, which governs the evolutionary timescale and which will remove essentially the whole envelope on timescales of about 10^4–10^5 years. Internally, however, the compact core evolves at its own pace. The hydrogen shell burning is periodically interrupted by a He-shell flash that generates a large energy excess. The ensuing thermal readjustment can induce contact between the H-poor, He- and C-rich intershell, such that the convective H-rich envelope becomes enriched in nuclear ashes (dredge-up). If efficient, the envelope chemical composition can reach a C/O ratio larger than 1, which has fundamental impact on the ensuing (chemical) evolution. Post-AGB stars bear witness of these processes.

2.1. Evolutionary Tracks

Founded on seminal papers of Paczyński (e.g., Paczyński 1970) and Iben (e.g., review by Iben & Renzini 1983), often-used evolutionary tracks, including AGB and post-AGB phases, were published for a whole range of initial masses by Schönberner (1983); Blöcker (1995); Vassiliadis & Wood (1993).

The tracks are not computed from first principles and the main uncertainties are linked to the prescription of the mass loss, also during the post-AGB phase. Because a post-AGB start is an extremely mass-concentrated object with an envelope mass of only a few 10^{-2} $M_\odot$, the detailed description of the badly known external post-AGB mass loss on top of the mass loss from the nucleosynthetic consumption ($\sim$$10^{-7}$ $M_\odot$ yr^{-1}) is crucial for the transition time estimates. Moreover, the mass-loss history on the AGB determines transition times since the length of the AGB evolution determines the internal structure of the remnant object. The integrated mass loss prescriptions are tested against the initial-final mass relation obtained by investigating WD in clusters (e.g., review by Weidemann 2000). Note that pre-AGB mass loss is thought to be significant for low initial mass objects ($M_i \sim 1\ M_\odot$) but insignificant for higher mass objects ($M_i \geq 3\ M_\odot$). The mass loss descriptions on the AGB used by Vassiliadis & Wood (1993) are, in general, lower than the ones of Blöcker (1995) making the final WD more massive for the same initial mass. On the contrary, the post-AGB mass loss adopted by Vassiliadis & Wood (1994) is lower making their transition times longer, certainly for the high mass end of the tracks. The constraints set by the dynamical ages of PNe prefer fast evolutionary timescales (e.g., review by Schönberner 1997).

To illustrate the expected luminosities and timescales of post-AGB objects, Figure 2 gives the tracks of Blöcker (1995) on which evolution times are tagged for tracks of a massive and a low-mass object respectively. Typical post-AGB stars are

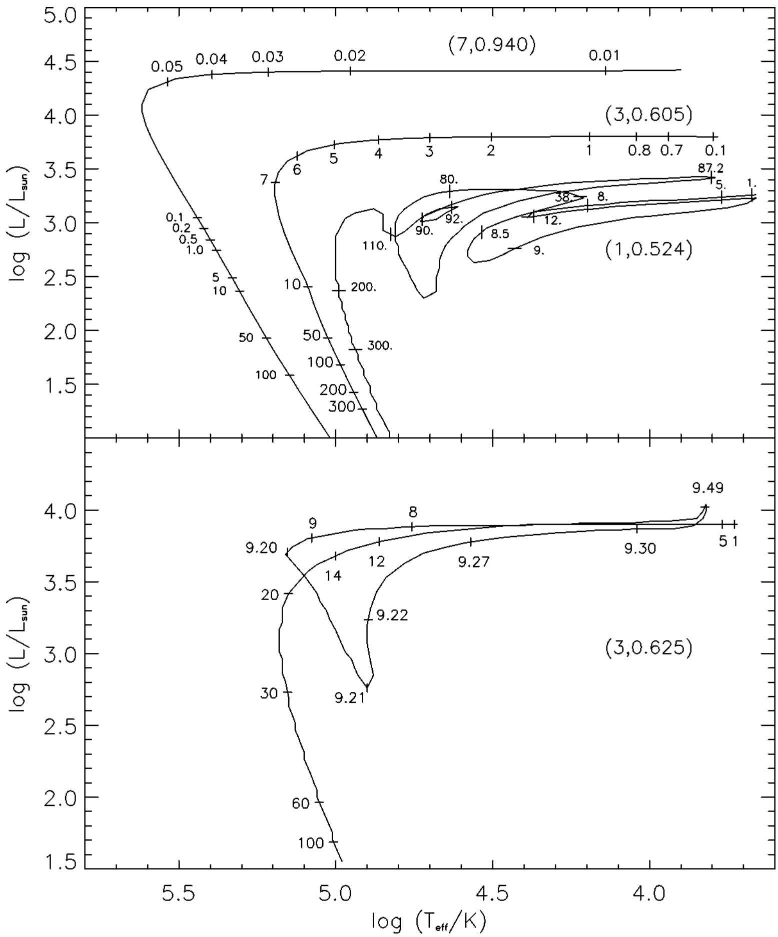

Figure 2 Evolutionary tracks of the final stage of stellar evolution from Blöcker (1995). In the upper panel three tracks are given with different inital-final masses of ($7M_{\odot}$,$0.940M_{\odot}$), ($3M_{\odot}$,$0.605M_{\odot}$) and ($1M_{\odot}$,$0.524M_{\odot}$) respectively. Tagged are units of 10^3 years. Note the fast evolution of the most massive model. The lower panel gives a model that suffers a late thermal pulse during its first post-AGB phase, which is to be expected when the post-AGB evolution begins close to the next thermal pulse. The object returns quickly to the AGB ("born-again"-AGB star) to cross the HR diagram for a second time. For the low mass objects, this born-again scenario can take place two times prior to reaching the White Dwarf cooling track (see lower curve upper panel).

expected to have luminosities around 10^3–10^4 $L_{\odot}$. The transition time is extremely short for the most massive objects ($\sim$30 years), which will still be embedded in their AGB dusty envelope prior to the onset of the PN stage. The obscuration of the dust will prevent optical identification of the central star. At the other mass extreme, the transition times are so slow that the circumstellar material will be too dispersed when the energetic inonizing photons are finally created, and no PNe is expected. The observational bias of post-AGB stars will therefore be toward lower mass objects. It is interesting to note that for some objects, like He 1357 (Parthasarathy et al. 2001) the onset of the PNe stage is probably witnessed in real time.

The succession of thermal pulses with or without dredge-up determines the characteristics of the core (and thus remnant product of the stellar evolution) but also the chemical content of the envelope. It is still a matter of debate how the dredge-up operates and for what core-envelope masses. Both the low and high mass limit for which stars become C-stars is uncertain but the low limit is around $M_i = 1.5\ M_\odot$. Constraints come mainly for the Carbon star luminosity function of the Large Magellanic Cloud, which indicates that dredge-up must be effective, also for low masses (e.g., Groenewegen et al. 1995, Marigo et al. 1999). Several evolutionary codes use different descriptions with overshoot (Mowlavi 1999, Herwig et al. 1997, Frost & Lattanzio 1996) or without (Straniero et al. 1997). Herwig (2000) uses convective overshoot not only in the envelope-core border, but also at the bottom of the He-flash convective zone, which generates an efficient dredge-up, even at lower masses and at solar metallicity. Because carbon stars are more numerous in reduced environments, it is generally accepted that the dredge-up is more efficient for a low initial metallicity (e.g., Groenewegen 1999).

The phasing of the thermal pulse cycle with respect to the onset of the post-AGB track is also important. It can be expected that about 70% of post-AGB stars are H-burning, 15% are He burning, and another 15% are both (e.g., Blöcker 2001). If the post-AGB evolution starts at $\geq$90% of the pulse cycle, the conditions are right to expect a final thermal pulse during the post-AGB phase. This can occur on the luminous horizontal part ("late thermal pulse"), or even on the WD cooling track, when the hydrogen shell burning is already extinct ("very late thermal pulse") (Herwig et al. 1999). Those pulses will inflate the envelope and generate a "born-again" AGB star (e.g., Schönberner 1979, Iben 1984). These objects evolve so fast that nonfatal stellar evolution can be witnessed on a human timescale. Section 6 focuses on these objects. Note that these are not marginal since about 10% of the AGB objects will suffer these late pulses.

2.2. Chemical Composition

The chemical composition of a post-AGB star should reflect the initial composition of the object, modulated by dredge-up processes of nucleosynthetic ashes from the stellar interiors. Because post-AGB stars are often of spectral type F–G, atmospheric molecular veiling is negligible, and the abundance of a broad range of chemical species, from CNO up to very heavy s-process elements can be obtained from atomic line spectra. As such, chemical studies of post-AGB stars are not only important to track the evolutionary nature of the object itself, but also to constrain chemical evolutionary models.

The AGB chemical evolutionary models play an important role in the interpretation of results and, apart for the yields of hydrogen and helium burning, also trans-iron elements are known to be produced. We just celebrated the fiftieth anniversary of the detection of technetium by Merrill (1952). Because the most stable isotope produced in the s-process of Tc (^{99}Tc) has a half-life of 2.1×10^5 years, this was the first observational evidence that low- to intermediate-mass stars are able to produce trans-iron elements during the AGB evolution.

The AGB nucleosynthetic models were extensively reviewed in this series by Busso et al. (1999). The models are based on post-processing in which a stellar evolutionary model is linked to an extensive nuclear reaction network. In the stellar interiors, the neutron irradiation induced nucleosynthesis is expected to be slow (s-process) compared with the β-decay of unstable isotopes so the heavy element nucleosynthesis follows the valley of stability in the nuclear chart. The small cross-sections around closed neutron shells are reflected immediately in the expected high abundances of these nuclides ($N = 50$ for Sr, Y, and Zr; $N = 82$ for Ba, La, Nd; up to the double magic ^{208}Pb, which marks the end of the s-process). The models of nucleosynthetic changes during the AGB evolution are complex and are related to the partial mixing zone in the intershell between the H-burning layer and the CO inert degenerate core. The introduction of protons into the intershell, rich in primary ^{12}C, is the seed of the s-process, and it is now generally acknowledged that the $^{13}C(\alpha,n)^{16}O$ reaction, burning during the interpulse period under radiative conditions (Straniero et al. 1995) is the main neutron source. The $^{22}Ne(\alpha,n)^{25}Mg$ neutron source is only important in massive AGB stars and will give only a marginal contribution to the s-process in the bulk of the AGB stars.

The main uncertainty in the theoretical models is the physical origin of the partial mixing of protons into the intershell (e.g., Herwig et al. 1997, Busso et al. 2001, Goriely & Mowlavi 2000, Lugaro et al. 2003) but there is general agreement that the formation of the ^{13}C-pocket is intimately related to the dredge-up episode after the thermal pulses. The most recent AGB models include differential rotation of the envelope-core interface (Langer et al. 1999). Whereas the rotational induced mixing is not efficient enough to produce a significant ^{13}C pocket, it can modulate the s-process nucleosynthesis by mixing part of the ^{14}N-pocket as neutron poison in the ^{13}C-rich layer (Herwig et al. 2003).

The most important parameter that governs the neutron irradiation is the profile of the p/^{12}C ratio. The nucleosynthesis itself is constraining the possible range in proton ingestion needed for efficient s-process nucleosynthesis and the resulting shape of the s-process overabundance distribution is strongly determined by the largest neutron exposure generated in the radiative intershell. Because the ^{12}C of the intershell is of primary origin, a metal deficient star will undergo a more efficient neutron nucleosynthesis per iron seed nucleus in the same p/^{12}C regime.

3. POST-AGB SEARCHES

Because the evolutionary phase is fast, post-AGB stars are rare. Systematic searches to identify post-AGB candidates were only performed when mid- to far-IR experiments were launched. The IRAS mission in 1983 was most successful in enabling systematic identification of post-AGB candidates and the ([12]–[25], [25]–[60]) color–color diagram has been used extensively as a basis for ground-based follow-up to identify objects between the locus of the PNe and the late-type AGB stars (e.g., Kwok et al. 1987, Volk & Kwok 1989, van der Veen et al. 1989, Manchado et al. 1989, Hu et al. 1993, García-Lario et al. 1997, Van de Steene et al. 2000). Most of these objects are optically rather faint since the selection criteria focus on the expected properties of the expanding dust-shell. The objects are therefore only known by their long IRAS names, providing a good test of one's memory. The central stars (if observed) cover the spectral type sequence from M to B. Among the B-star sample (Parthasarathy et al. 2001), some display evidence for a fast evolution to the PN stage.

Other systematic searches focused on cross-correlating optical catalogues with the IRAS point-source catalogue in search of luminous objects with an IR excess due to thermal radiation of circumstellar dust (Hrivnak et al. 1989, Pottasch & Parthasarathy 1988, Trams et al. 1991, Oudmaijer et al. 1992). These objects display a wider variety of IR-colors and are scattered over the whole IRAS color-color diagram. The high-galactic latitude giants (HR 6144; HD 161796; 89 Her), identified by Bidelman (1951) during his spectral classification program of Miss Paynes catalogue of anomalous luminous stars, were recovered in these searches by their IR excesses, and it is now generally acknowledged that F-G supergiants far from the Galactic plane are old and hence low-mass objects in their post-AGB evolutionary stage.

Confusion may come from other objects with circumstellar dust, and thus similar SEDs, which are mainly young stellar objects (Waters & Waelkens 1998) or massive post–red-giant stars. The distinction between the latter and genuine post-AGB stars is, without luminosity constraints, not always straightforward. This is illustrated by the fact that HR 6144, the only one without detected IR-excess from Bidelmans original trio, is sometimes classified as a massive object (Venn 1995).

The post-AGB tracks cross the high luminosity end of the pop II Cepheid instability strip (e.g., review by Wallerstein 2002), and the variable class of the RV Tauri stars are generally acknowledged to harbor post-AGB objects. The main indication was that many RV Tau stars display both a near-IR excess (Gehrz 1972, Evans 1985) and a far IR-excess as found by IRAS (Jura 1986). RV Tauri stars display complex light curves with alternating deep and shallow minima with often intermittent lower amplitude irregularities. The high luminosity was corroborated by the detection of RV Tauri stars in Globular Clusters (GC) and in the Large Magallanic Cloud (LMC) (Alcock et al. 1998), where the proposed period-luminosity relation for pop II Cepheids also covers the more luminous RV Tauri stars. Other variable stars linked to a post-AGB evolutionary stage are the R CrB stars. These rare objects (about 30 are known in the Galaxy) are hydrogen poor supergiants that display in their light curve sudden deep drops, up to eight magnitudes, which are caused by dust obscuration in the line of sight (e.g., review by Clayton 1996) but also display pulsations in their phases of light maxima. They are often related to late-flash scenarios (see Section 6), but the alternative as the product of a coalescence of a wide dwarf system is not excluded. Surprisingly many R CrB stars were found in the LMC as a byproduct of the MACHO experiment and, besides pinning down the absolute magnitude range ($M_V = -2.5$ to -5), this indicated that cool R CrB are more common than expected from Galactic counts (Alcock et al. 2001). Note that none (except maybe one) of the R CrB is known to reside in a binary system.

Hot, B-type post-AGB stars were discovered in systematic studies of the B-star population in the Galactic Halo. Because the effective temperature and surface gravities expected from the evolutionary tracks are similar to B-stars evolving from the main sequence, detailed chemical studies are needed to select the post-AGB objects (e.g., McCausland et al. 1992, Moehler & Heber 1998). Subsequent IR measurements revealed that the more massive (meaning, more luminous) objects still display IR excesses (Conlon et al. 1993a), and the post-AGB nature was confirmed by the detection of a nebula around one of the objects LSIV-12^{deg}111 (Conlon et al. 1993b). UV-bright objects also exist in GCs, the most luminous of which evolve along a post-AGB evolutionary track (see review by Moehler 2001). These are the GC analogues of the field B-type post-AGB stars.

Field post-AGB stars are generally too far away to yield reliable parallaxes and hence luminosities. A field post-AGB star in a binary with a Mira companion (HD 172481) is one noticeable exception (Reyniers & Van Winckel 2001, Whitelock & Marang 2001) and the period-luminosity relation of the Mira yields a luminosity of $L \sim 10^4\ L_\odot$. In GC, also F-G type post-AGB stars were recovered for which the luminosity is more easily measured. The most famous is RAO24 in ω Cen (e.g., Gonzalez & Wallerstein 1996). In the GC NGC5986, two A-F supergiants are discovered (Alves et al. 2001). Because the turn-off mass is a good estimate of the initial mass of the post-AGB stars, the post-AGB luminosity function is sharply peaked and those three, yellow post-AGB stars yield a $M_V = -3.28 \pm 0.07$. Because the large Balmer jump of these stars is well traceable with a good choice of filters, more extensive specific searches should be initiated to discover post-AGB stars in external galaxies. In a preliminary result, Bond & Alves (2001) report upon the detection of yellow post-AGB stars in M31 and its dwarf elliptical NGC 205 yielding a good reproduction of the Cepheid distance to M31 using the abovementioned distance indicator.

The statistical research based on population studies of post-AGB stars are scarce, and studies of individual objects prevail. The main problem is often to discover how representative a certain characteristic is in the complete picture of stellar evolution since anyones' pet objects are not necessarily very representative examples of a "typical" post-AGB evolution. In a recent literature compilation, Szczerba et al. (2001) discuss 220 post-AGB stars from different samples with different selection biases. Spectral types B and F dominate. The galactic distribution shows a concentration toward the plane with a significant representation at higher latitudes and without a specific concentration toward the Galactic center. In the IRAS color-color diagram, the objects are rather dispersed over the diagram with a concentration toward the PN box.

4. CENTRAL STARS: ABUNDANCES

When the central star is directly observable, study of the photospheric conditions become possible, often even with high-resolution spectroscopy. The fundamental parameters of the photosphere are then traceable but also the chemical composition. In recent years, it became clear that the chemical diversity in post-AGB stars is larger than anticipated with only a subsample displaying the chemical richness expected from AGB chemical models with proton engulfment in the intershell.

4.1. s-Process: The Haves

Strong s-process lines were first discovered in HD 56126 by Klochkova (1995) and since then several studies of the photospherical chemical composition focused on s-process abundances in field post-AGB stars. An overview is given in Reddy et al. (2002) and Van Winckel (2003).

Although in absolute abundance, the s-process elements still occur in trace amounts, the overabundance relative to the solar value was found to be large with e.g., the [Zr/Fe] ratio between $+1$ and $+2.4$. The atomic spectrum of some s-process species is so rich that they completely dominate the stellar spectrum (Figure 3). Unfortunately, these individual studies lack homogeneous atomic data, and the uncertain oscillator strengths (f-values) have a direct influence on the quantitative abundance estimates. Several groups use quite different values (easily up to 0.3–0.5 dex difference in log gf) for the lines making that quantitative comparison on a 0.2 dex level (typical uncertainty on the abundance results based on high-resolution, high-quality data) with chemical AGB model calculations still somewhat hampered.

The s-process enriched objects cover a spread in metallicity between [Fe/H] $=$ -0.2 to -1.0, indicating they are of a low-mass nature. The C/O ratio estimates based on atomic lines is not well constrained but for those objects where O-lines are available, the C/O is clearly larger than one. The s-process enriched objects are therefore post–metal-poor Carbon stars. This is corroborated by the presence of a 21 μm IR emission feature associated with C-rich circumstellar material (Kwok et al. 1989, Section 5) in all sources for which the data are available, together with the presence of circumstellar electronic transitions of C_2 and C_3 (Hrivnak 1995, Bakker et al. 1997) and the often strong HCN detections. Based on extremely high resolution data, a $^{12}C/^{13}C$ ratio of 72 ± 26 was deduced for HD 56126 by Bakker & Lambert (1998), and for other objects lower limits of typically $^{12}C/^{13}C \leq 20$–25 were deduced (Reddy et al. 2002).

In a strict homogeneous study (see Figure 4), there emerges a clear relation between neutron irradiation and the s-process overabundance, measured by the ratio of heavy Ba-peak elements to lighter Sr-peak elements (Van Winckel & Reyniers 2000). This indicates that the dredge-up itself is indeed strongly linked to the proton ingestion into the intershell. The s-process signature is found to be somewhat dependent on the metallicity as well, but the spread is large and certainly

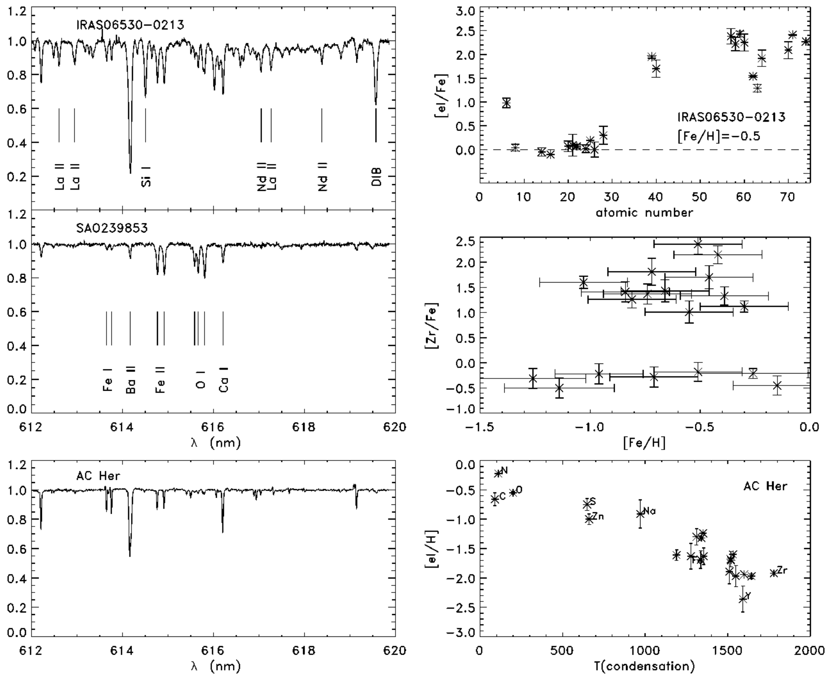

Figure 3 Illustrative spectra of the diversity of chemical patterns observed in post-AGB objects. In the left panels, normalized sample spectra are shown. In the right, their typical abundance characteristics. The top star is IRAS06530-0213 ([Fe/H] = −0.5), one of the most s-process enriched objects known (Reyniers 2002). The optical spectrum is completely dominated by atomic transitions of s-process species. In the middle panel is shown that the s-process enhanced objects (large [Zr/Fe] abundance ratio) cover the same metallicity as the non-s-process enhanced objects, without a smooth overlap of both categories: either an object is strongly enhanced, or it is not enhanced at all. In the lower panel the abundances of the depleted star AC Her ([Fe/H] = −1.5) are shown Van Winckel et al. (1998); Giridhar et al. (1998). The star is cooler than the upper two objects. The main characteristic of depleted objects is that the underabundances scale with the condensation temperature of the element. [Zn/Fe] and [S/Fe] are important abundance ratios.

intrinsic (Van Winckel & Reyniers 2000, Reddy et al. 2002). To understand these different compositions of similar stars with comparable metallicity, one needs to invoke a spread in neutron nucleosynthesis efficiencies and hence ^{13}C pockets.

Li production in AGB stars is well documented, both observationally (Smith & Lambert 1989, Plez et al. 1993, García-Lario et al. 1999) and theoretically by a process called hot-bottom burning (Lattanzio & Forestini 1999), but this seems to work only for intermediate-mass AGB stars. The high Li abundance found in the

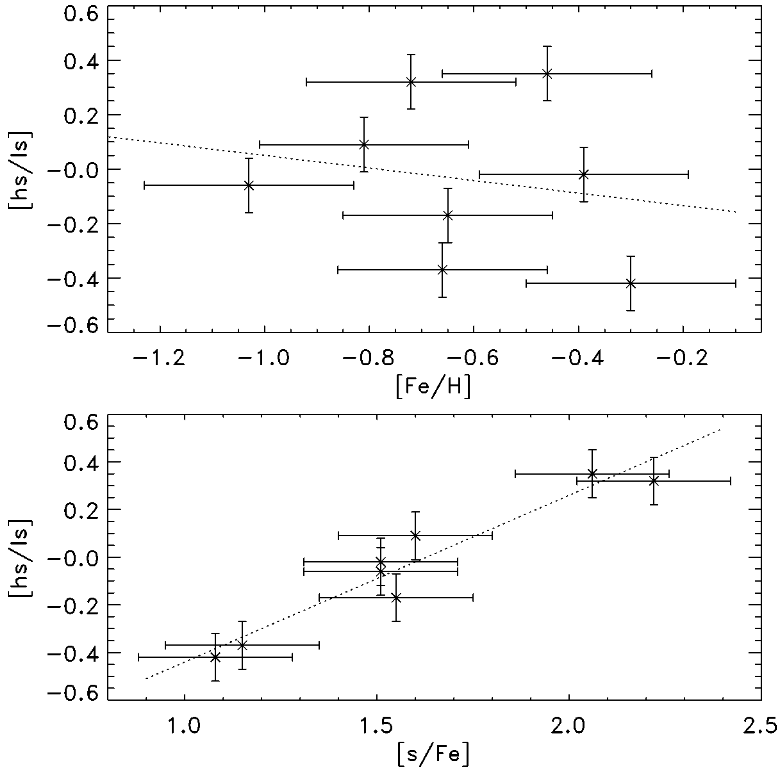

Figure 4 Homogeneous studies of the s-process enriched post-AGB stars show that the expected correlation between the [hs/ls] index with metallicity is hardly present (*upper panel*). The dotted line represents the least squares fit ([hs/ls] = − 0.23[Fe/H] − 0.18) with correlation coefficient of − 0.19. The lower panel shows the very good correlation between the total s-process enrichment, ([s/Fe]) and the characteristics of the internal s-process nucleosynthesis ([hs/ls]) with a least squares fit of [hs/ls] = +0.70[Fe/H]−1.14, yielding a correlation coefficient of +0.96. The data are from Van Winckel & Reyniers 2000 and Reyniers 2002.

low mass, s-process enhanced stars (e.g., Reddy et al. 2002) came therefore as a surprise. Recent new atomic data of ionized lanthanides showed, however, that the Li-line was misidentified and was due to an ionized cerium transition (Reyniers et al. 2002). Complete line-lists of neutral and ionized s-process lines with reliable atomic data are certainly needed and are gathered or in the making (Kupka et al. 1999, Biémont et al. 1999).

Two remarkable post-AGB candidates do exist with clear Li enhancements: the pop II Cepheid HR 7671 (Luck et al. 1990, Reyniers 2002) and the binary HD 172481 (Reyniers & Van Winckel 2001). The former has no detected IR-excess, is metal poor [Fe/H] = −1.1, and carbon poor ([C/Fe] = −0.3), and its post-AGB nature is questionable because the pulsation period of 25 days points to a lower luminosity. The latter has a Mira companion (Whitelock & Marang 2001), is also metal deficient ([Fe/H] = −0.6), and not C-enhanced ([C/Fe] = 0.0). Both display evidence for weak s-process enhancement ([Y/Fe] $\sim$ +0.5) while in both objects the Li overabundance is large: [Li/H] = +1.3, and [Li/H] = +2.5 respectively. Clearly both stars are low-mass objects for which the chemical composition is not understood.

For strong neutron irradiation, a leakage from the Ba-peak toward the Pb-peak is expected theoretically (Goriely & Mowlavi 2000, Busso et al. 2001) and recently also confirmed observationally in some (but not all) low metallicity cool extrinsic objects (Van Eck et al. 2001, 2003) for which large Pb abundances were detected. Lead itself is difficult to observe in the warmer intrinsic post-AGB objects, but strong overabundances of the very heavy elements gadolinium (Z = 64), ytterbium (Z = 70), lutetium (Z = 71), and maybe also tungsten (Z = 74) were detected in high quality data on IRAS06530-0213, IRAS08143-4406, and IRAS05341+0852 (Reyniers 2002) (Figure 3). Although the neutron irradiation in these object was clearly very strong, the metallicities are not extremely low [Fe/H] = −0.5, −0.4, and −0.7 respectively, so even at moderate metallicities Pb production is expected in some objects, depending on the neutron production efficiency in the intershell.

Direct comparison between the post-AGB chemical studies and the intrinsic cool AGB objects is not straightforward because most AGB stars studied are of solar metallicity. The M-MS-S-SC-C spectral sequence is thought to be mainly dependent on the increasing C/O ratio (e.g., Lambert et al. 1995). In addition, the increasing C/O ratio seem to correlate well with an increase in s-process enrichment (e.g., Smith & Lambert 1990). Recent results on solar metallicity C-stars (Abia et al. 2001) indicate, however, that older s-process abundance determinations in SC stars (Abia & Wallerstein 1998), and certainly carbon stars (Utsumi 1985), were strongly overestimated. The molecular veiling is so strong in C stars and the CNO abundances have such an impact on the model atmosphere structure that only now have more precise abundances of trace elements become available in the cool AGB stars. The difficulty in obtaining quantitative s-process abundances for AGB C-stars is illustrated by the fact that for the low metallicity C-star V CrB, the analysis of Kipper (1998) and Abia et al. (2001) differ by 1.2 dex in [ls/Fe]! We can conclude that the 21 μm post-AGB stars are clearly the most s-process intrinsically enriched objects known to date and their spread in metallicity combined with the wide range in elemental abundance determinations (from C to Lu) make them ideal sources to constrain AGB chemical models.

4.2. s-Process: The Have-Nots

Photospheric s-process overabundances are certainly not a universal property of post-AGB stars. They were, until now, found only in objects with clear C-rich dust characteristics, except for the two objects HR 7671 and HD 172481 mentioned above. In particular the 21 μm stars are strongly s-process enhanced. For objects with O-rich dust and a double peaked SED, the photospheric chemical signature is less easy interpretable in the framework of the chemical AGB theory.

Luck et al. (1990) pointed out that the high latitude A-F supergiants HR 6144, HD 161796, and 89 Her are metal poor ([Fe/H] ~ -0.4), slightly carbon enhanced ([C/Fe] $\sim +0.3$), and more strongly N-enhanced ([N/Fe] $\sim +0.9$ to $+1.1$), indicating that both hydrogen- and helium-burning products were mixed to the stellar surface. s-process elements were not found to be enhanced and even deficient in some cases. The post-AGB status of HR 6144 has been questioned since then (Venn 1995), but the double peaked SED and kinematical properties of HD 161796 and 89 Her are clear indications that these are genuine post-AGB objects. The lack of a s-process signature was found in more post-AGB stars with clear double-peaked SEDs and even lower metallicity. HD 133656 ([Fe/H] $= -1.0$, [C/Fe] $= +0.3$), SAO 239853 ([Fe/H] $= -0.8$, [C/Fe] $= +0.4$), (see Figure 3) are good examples (Van Winckel 1997). A subtle C-enrichment is present and the chemical signature does not point to only enrichment of CNO-hydrogen-burning products. The chemical composition of these objects is, therefore, not well understood. Note that often high N-overabundances in the [N/Fe] $= +0.2$ to $+1.0$ range are reported in both C-rich and O-rich objects. These are upper limits because the non-LTE sensitive N lines yield upper limits in a LTE approach and correction is about 0.3 dex for F-type supergiants Venn (1995). A non-LTE analysis of N in post-AGB stars has yet to be performed.

The non-s-process enriched objects show the same metallicity spread in the [Fe/H] $= -0.3$ to -1.0 range, a similar double peaked SED (Van Winckel 2003), but the O-rich nature of the dust corroborates the absence of an efficient third dredge-up in these sources. It is surprising that no mild s-process overabundances are detected either, and even s-process deficiencies are reported. A post-AGB star is C-rich and strongly s-process enhanced, or it is O-rich and no s-process overabundances are detected (see Figure 3). AGB models of low-mass objects indicate that the third dredge-up only occurs above a certain initial mass limit with a lower metallicity favoring dredge-up. The distribution in SED characteristics and metallicity among the haves and the have-nots is for the field post-AGB stars, however, similar with a lack of intermediate enriched objects. To know whether this reflects a true distribution, or is caused by a bias in the selection criteria remains to be studied. Large aperture telescopes equipped with high resolution spectrographs enable one to study fainter, more dust-enshrouded objects and will allow a more complete picture of their chemical diversity.

An illustration of the fact that chemical composition of an O-rich object is difficult to interpret is HD 179821, a bright star (m(v) = 8.1) with a strong IR excess and a wealth of observational constraints: the V_{lsr} is 105 km s^{-1} (Zuckerman & Dyck 1986); the circumstellar envelope is expanding at 34 km s^{-1} and is resolved in mid-IR, near-IR, and CO (Hawkins et al. 1995, Kastner & Weintraub 1995, Bujarrabal et al. 1992); and the object is mapped in interferometric OH-maser measurements (Gledhill et al. 2001). Despite several chemical studies (Reddy et al. 1999, Thévenin et al. 2000), it is yet a matter of debate whether this object is a massive supergiant about to explode as supernova (e.g., Jura et al. 2001) or a low-mass object in its post-AGB phase of evolution (e.g., Josselin & Lèbre 2001).

4.3. B-Star Post-AGB Objects

The low-metallicity B-star post-AGB population in the halo shows peculiar chemical patterns with the main characteristic a solar He content, deficiency of N, O, and the intermediate-mass elements Mg, Al, Si, and S in the range -0.5 to -2.0 compared to solar and an even larger C deficiency (McCausland et al. 1992, Kendall et al. 1994, Moehler & Heber 1998), even though the C-determinations based on the 4267 Å line of the former paper may be underestimated (Conlon et al. 1993b). N is, in general, less deficient relative to the other elements. Direct Fe measurements are scarce in these objects but, if present, reveal a significant deficiency indicating a pop II chemical composition (Conlon et al. 1993b). The abundance pattern is similar to that observed in the halo planetary nebula such as DDDM-1 (e.g., Conlon et al. 1993b) and BD $+33^{\circ}2642$ (Napiwotzki et al. 1994). As stated earlier, these objects most likely evolve on the lower mass post-AGB tracks and are certainly not post third dredge-up objects. The C/N ratios are consistent with CN cycling, the N/O ratios in some objects are not (Moehler & Heber 1998).

Interestingly, the UV bright giants in the GC show the same abundance trends as the field post-AGB B stars with a stronger C deficiency than the N, O and intermediate mass elements. These abundances are best explained by CN cycling material mixed in a pop II object (Conlon et al. 1994, Moehler et al. 1998, Mooney et al. 2001). Also here, Fe lines are generally not available in the optical spectra of these objects. Recent high quality HST UV-spectra indicate the Fe abundance to be surprisingly smaller than the metallicity of the parent GC for two objects [Barnard 29 in M13 and ROA5701 in ω Cen (Moehler et al. 1998)], and a scenario needs to be invoked to decrease the Fe abundance during evolution.

The large C deficiencies are generally not found in the cooler F-G type post-AGB star, and it is unlikely that there is an evolutionary link between both classes. A noticeable exception could be HD 107369 ([Fe/H] $= -1.1$, [C/Fe] < -0.2, [N/Fe] $= +0.4$) (Van Winckel 1997). The object has no detected IR excess, but its low metallicity low gravity, F-spectral type are indicative of an evolved nature of a low mass object.

4.4. Depletion

The object BD$+39.^{\circ}4926$ has long been known for its enigmatic abundances: an extremely low iron content ([Fe/H] $= -2.9$) coupled with near solar abundances of C, N, and O. Similar, but less extreme deficiencies were found for HD 46703 (Bond & Luck 1987) who noticed a large sulfur overabundance relative to other α-capture elements ([S/Fe] $= +1.3$). Even more extreme examples were soon found in HR 4049 ([Fe/H] $= -4.8$, [C/Fe] $= +4.6$, [N/Fe] $= +4.8$, [O/Fe] $= +4.5$, [S/Fe] $= +4.4$) (Lambert et al. 1988, Takada-Hidai 1990, Waelkens et al.

1991), HD 52961 ([Fe/H] = −4.8, [C/Fe] = +4.2, [N/Fe] = +4.3, [O/Fe] = +4.3, [S/Fe] = +3.7) (Waelkens et al. 1991). The last object has more zinc than iron in absolute number!

Following the suggestion by Venn & Lambert (1990) who noticed the similarity of the chemical pattern to the gas-phase abundances of the ISM, Bond (1991) proposed that iron is not primordial, but selectively removed by dust formation in these post-AGB stars. This received strong support by the detection of Zn-lines in HD 52961 (Van Winckel et al. 1992) yielding an abundance ratio of [Zn/Fe] = +3.1! Because Zn has the same nucleosynthetic history as Fe, but a much lower dust condensation temperature (e.g., Lodders & Fegley 1998), the chemical pattern must be determined by a chemical rather than a nucleosynthetic process. The basic scenario involves a chemical fractionation caused by dust formation in the circumstellar environment; a decoupling of the gas (which is depleted in refractory elements) and the dust, probably by radiation pressure on the dust particles, which is then followed by a reaccretion of the "clean" gas. The C/O ratio will be close to 1 since CO will be an abundant molecule in the accreted gas and C-enhanced spectral signatures can be observed. The most characteristic chemical signatures of this depletion of refractories are high [Zn/Fe] and [S/Mg,Si,Ca] ratios because a high [C/Fe] ratio alone can point as well to an efficient dredge-up and [α/Fe] ratios of about +0.4 to +0.6 are observed in unevolved metal-poor stars. Note that the s-process elements are refractory, so the chemical composition of the circumstellar dust is the best tracer for eventual AGB enrichment.

Mathis & Lamers (1992) have discussed several processes in which separation of circumstellar dust and gas may operate, and Waters et al. (1992) added that the most favorable circumstances may occur if the circumstellar dust is trapped in a stable disc. For post-AGB stars, the presence of a circumsystem disc implies binarity and the observational basis of this process was that all strongly depleted objects known at that time were found to be binaries with strong evidence for some that the dust was indeed in a flattened geometry (Van Winckel et al. 1995). For the first known depleted star (BD + 39.$^\circ$4926), an IR-excess has not been detected, however.

The observational restriction that the depletion process was only active in binaries became less evident when it turned out that depletion is a much more frequent phenomenon. In a series of papers (Gonzalez & Wallerstein 1994; Giridhar et al. 1994, 1998, 2000; Gonzalez et al. 1997a,b) it was shown that depletion patterns are frequently observed in RV Tauri stars. In the original spectral classification of Preston et al. (1963) the "weak-lined" RV Tau stars with enhanced CN and CH-lines all turned out to be depleted rather than C-enhanced by dredge-up processes. Giridhar et al. (2000) point out that the depletion process turns out to be inactive for pop II initial abundances. Several RV Tauri stars with very different levels of depletion are indeed found to be binaries by long-term radial velocity measurements [U Mon, Pollard & Cottrell (1995), AC Her, Van Winckel et al. (1998), En Tra, Van Winckel et al. (1999), RU Cen and SX Cen, Maas et al. (2002b)], but it is certainly not generally accepted that all depleted RV Tau stars reside in binaries.

Based on high-resolution UV and optical spectra, Napiwotzki et al. (2001) concluded that the chemical composition of the cool halo PN BD$+33^{\circ}$2642, (with [Fe/H] $= -1.2$ but [Ar/Si] $= +0.8$ and [S/Si] $= +0.4$) is also best explained by depletion. This star was found to be most likely a binary, but the orbital parameters are not yet detected. It seems that the effect of depletion can last until the PN phase of the central star. Whether depletion can explain the low metallicity of the GC post-AGB stars as suggested by Moehler et al. (1998) remains an open question and needs accurate determination of the abundances of nonrefractory elements like S and Ar in comparison with refractories.

5. CIRCUMSTELLAR ENVIRONMENT

5.1. Imaging

Almost all talks, professional and popular alike, on the morphology of PNe start with a display of the *HST* pictures showing the astounding variety of ordered complexity of the interference filter images of the PNe, followed by the contradictory finding that on the AGB, the mass-loss is found to be spherically symmetric: during the transition time, the star and circumstellar envelope must undergo fundamental and rapid changes in structure, mass-loss mode, and geometry that are still badly understood. Because the shapes and shaping of PNe was reviewed in great detail in last years' issue of the *Annual Review of Astronomy and Astrophysics* by Balick & Frank (2002) it will not be repeated here. Only the most important observational findings concerning post-AGB nebular morphologies and dynamics are restressed.

The debate on what physical mechanisms are driving the morphology changes gained even more impetus from the finding that resolved post-AGB stars display a surprisingly wide variety in shapes and structure, not traced in emission-line filters, like in PNe, but in scattered light. Asphericity is the rule, bipolarity very common, multipolar collimated outflows and evidence for disk collimation not exceptional. For a nice review (and a nice aesthetic experience), see Sahai (2001). Disks (or dusty tori) are observed, not only by excessive line-of-sight extinction but also in scattered light (Sahai 1999, Kwok et al. 2000) and in OH interferometric maps (Zijlstra et al. 2001). In a *HST* snapshot survey, Ueta et al. (2000) resolved 21 of 27 sources all showing asphericity. They bifurcate the resolved objects in star-obvious low-level elongated nebulae (SOLE, 11 sources) and dust-prominent longitudinally extended nebulae (DUPLEX, 10 sources). The acronyms are not referring to the single or binary nature of the central star but to a difference in optical thickness of the circumstellar shell with increasing pole-to-equator density contrast. This was corroborated also by high spatial mid-IR imaging (Meixner et al. 1999). Although projection effects certainly play a role (Su et al. 2001), the main division between the two groups are intrinsic with the former evolving from lower mass progenitors than the latter (Meixner et al. 2002), similar to what is observed for the bipolar mature PNe compared to their round and elliptical peers (e.g., Corradi & Schwarz 1995).

The object that displays best the panoply of different structural ingredients, some of which are also displayed in other nebula, is AFGL2688 (the Egg Nebula). Although it is one of the first transition objects discovered (Ney et al. 1975), it is still rather badly understood. The central object of F-spectral type is observed only in scattered light and lies hidden in an optically thick dusty disk. The bipolar nebula is a pair of “searchlight beams” escaping from the poles of the disk (Figures 1–2 of Sahai et al. 1998). The nebula is famous for the numerous concentric arcs around the resolved center, indicating episodic spherical density enhancements with dynamical intervals of 150 to 450 years. Other nebula displaying these arcs can be found in Hrivnak et al. (2001); Balick et al. (2001). Although the nature of these is still a matter of debate (Simis et al. 2001, Soker 2002), the spherical symmetry indicates the process antedated the formation of the central thick dusty torus in AFGL2688. The inner structure is even more complex with a pair of high-velocity polar outflows resolved in several collimated jets traced in CO (Cox et al. 2000). The edges are marked by collisionally excited H_2 emission (Sahai et al. 1998). Even more surprising, the same papers show that in the equatorial direction, several distinct jets are detected both in CO and H_2. VLA detection at cm wavelength resolves the source, and the elongation falls between the polar and equatorial CO jets (Jura et al. 2000). The outer structure is large and scans at 120 and 180 μm revealing faint extended emission up to 350–400$''$ from the central source (Speck et al. 2000). NICMOS high spatial resolution imaging revealed the possible companion in a wide orbit (Weintraub et al. 2000), but it is often assumed that the system also contains a close binary. Clearly much has to be learned yet from this often labeled prototypical transition object.

The kinematical information in post-AGB nebulae is also of prime importance in understanding the physical mechanisms involved. An ultrafast high velocity collimated outflow reaching 2300 km s^{-1} is traced in H_α in the post-AGB object He3-1475 (Sánchez Contreras & Sahai 2001), but high velocity outflows are also found in molecular CO gas. The extensive review by Bujarrabal et al. (2001) shows that a fundamental property of the fast bipolar outflow, detected in 25 of the sample of 29 post-AGB stars with high quality data, is that it carries too much linear momentum (up to 1000-times excess) to be driven by radiation pressure! Other, but badly understood, momentum sources have to be explored, with binarity induced accretion energy only one of the possibilities.

The main observational conclusion is that the transition from isotropic to highly nonisotropic circumstellar morphology is situated at the very end of the AGB or early post-AGB phase but the mechanisms involved are not well documented (more detailed reading in Balick & Frank 2002). The understanding of these mechanisms will be certainly an important issue for many years to come.

5.2. Thermal Emission from Dust

Driven by the spectral capabilities of ISO, the past years were characterized by a rich mutual stimulus of laboratory research on dust species, and studies of the many solid state features in the mid- to far-IR spectra of dust enshrouded objects. The resonant vibrations of solid state particles are in the mid-IR spectra, and these features are an important diagnostic tool for the chemistry, condensation sequence, size, and shapes of circumstellar dust grains. Mainly thanks to ISO, asteromineralogy is a rapidly evolving science with very important input from the meteoritic community.

In post-AGB stars we witness the combined effect of the gradual hardening of the stellar radiation of the central star and the expansion of the detached dusty envelope that results in considerable modification of the dust compositions, e.g., several solid state bands are observed only in post-AGB stars. The post-AGB evolution is a short yet important phase in our understanding of circumstellar chemistry. In some cases shock-induced chemistry is observed caused by the impact of a faster wind on the slower previous stellar mass loss. When the star becomes hot enough, the photodissociation region (PDR) will allow ion-based chemistry.

The C/O ratio of the mass-losing AGB star is the most important chemical signature. Because of the stability of the CO molecule, the condensation sequence is vastly different in C- or O-rich environments (see Figure 5).

For the C-rich AGB stars, the 11.3 μm amorphous SiC feature is a prominent IR-signature together with the broad and often strong 30 μm feature discovered by Forrest et al. (1981). The latter is also strong in post-AGB stars [see Figures 1, 5] and PNe but with strongly varying band shape, position, and strength. Often a significant portion of the total IR-luminosity is emitted in the 30 μm solid state band. The feature is resolved and a different component peaks at 26 μm (Hrivnak & Lu 2000). In a detailed analysis of a range of objects (from AGB to PNe), Hony et al. (2002) could fit the feature taking into account only MgS, an identification originally proposed by Goebel & Moseley (1985), with different grain-shape distributions and grains out of temperature equilibrium with the surrounding material.

A strong dust feature solely observed in C-rich post-AGB stars is at 21 μm and was discovered by Kwok et al. (1989). The strength of the feature is strongly variable from one source to another (see Figures 1, 5), but the profile is remarkably constant (Volk et al. 1999). Several carriers were proposed (e.g., Hony et al. 2003), but an excellent spectroscopic match was found by lab measurements of resonances of TiC nanocrystals (von Helden et al. 2000). TiC will condense in a early stage in the (equilibrium) condensation sequence (Lodders & Fegley 1998), and was found in the center of pre-solar grains recovered from the Murchison meteorite as nucleation center for graphite grains (Bernatowicz et al. 1996). This identification has, however, strong astrophysical implications because Ti is rare in the metal poor 21 μm stars. The formation itself, but also the strength of the feature implies a high density during the formation epoch which implies mass-loss rate estimates on the order of $\geq 10^{-3}\ M_{\odot}\ \mathrm{yr}^{-1}$! Since the mass of the envelopes around 21 μm stars are between 0.1–0.5 $M_{\odot}$ (Meixner et al. 1997), the high mass loss phase would exist only a hundred years. Despite earlier suggestions, the 21 μm feature is also weakly observed in PNe with [WC] central stars indicating the carrier can survive the harsher radiation field (Hony et al. 2001). The photospheres of post-AGB stars with a circumstellar 21 μm feature are also C-rich with strong enhancements of

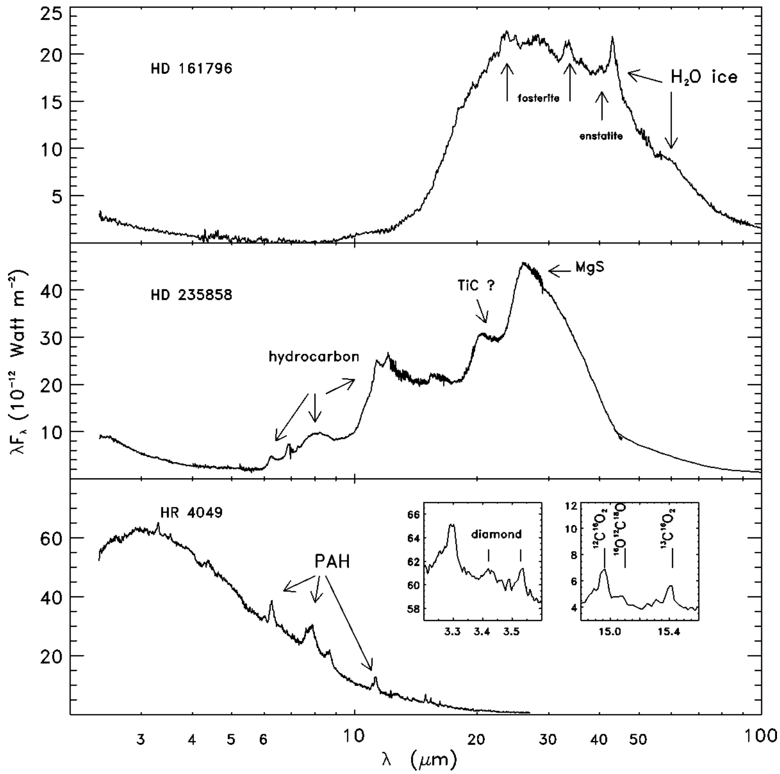

Figure 5 Illustrative spectra of circumstellar environment of post-AGB stars; an O-rich (*top*, HD 161796); a C-rich (*middle*, HD 235858); and one with mixed chemistry (*bottom* HR 4049). In the top panel, the different crystalline dust compostion signatures are indicated: fosterite, ensatite, and water ice. The bulk of the silicate dust is, however, in amorphous form (Hoogzaad et al. 2002). The lower panel is a C-rich dust envelope, with plateau emission of C–C and C–H bonds of hydrocarbons (Kwok et al. 2001, Hony et al. 2003) . At longer wavelengths, the 21 μm band, which is attributed to TiC, and the "30" μm emission feature attributed to MgS are apparent. The bottom panel shows the circumstellar spectrum of the enigmatic binary HR 4049. The continuum is well fitted with a pure, single-temperature black body, which constrains strongly the circumstellar physics (Dominik et al. 2003). The PAH features are strong, and in the inserts, the diamond (Geballe et al. 1989, Van Kerckhoven et al. 2002) and CO_2 (Cami & Yamamura 2001) features are shown.

s-process elements (see Section 4), and because most objects also show electronic transitions of C_2 and CN in their optical spectra (Bakker et al. 1997), they are considered typical (albeit metal-poor) post-Carbon stars.

In O-rich post-AGB stars (see Figure 5), the silicates dominate with the famous 9.7 and 18 μm broad feature of amorphous silicate. But also for those objects, the IR-spectra of ISO turned out to be much richer than anticipated, and narrower features were detected and identified as arising from crystalline silicates. The Mg-rich end-members of olivines (Mg_3SiO_4) and pyroxenes ($MgSiO_3$) prevail (Waters et al. 1996, Molster et al. 2002a) with strong additional features and complexes at 23.5, 27.5, 33.5, 40.8, 43.3, and 60 μm (e.g., Waters et al. 1996, Molster et al. 2002a, Hoogzaad et al. 2002). At longer wavelengths, the strong broad bands of crystalline water ice at 43 and 60 μm were discovered first in the post-AGB star nicknamed “Frosty Leo” (Forveille et al. 1987), but since then they have been discovered in other O-rich evolved objects, from OH/IR stars to very hot PNe (e.g., Barlow 1998, Sylvester et al. 1999, Molster et al. 2001a).

The degree of crystallinity of the silicates is typically on the order of 5–10% for evolved objects, but where there is evidence that the dust resides in a disk, the crystallinity fraction is higher (Molster et al. 1999, 2002c) up to an exceptional 60–80% (Molster et al. 2001a). Because it is unlikely that the dust was formed above the glass temperature in these evolved objects, a cool but badly understood crystallization process is suspected (Molster et al. 1999). More tentative identifications in post-AGB stars include diopside ($CaMgSi_2O_6$) and silica (SiO_2) (Molster et al. 2002a).

Because the chemical evolution from O-rich to C-rich is predicted to take place on the AGB, the dust surrounding post-AGB stars and PNe should be either O-rich or C-rich with a central star of similar chemical composition. One of the unexpected results of ISO was the detection of evolved objects for which both O-rich silicates were detected in combination with C-rich features.

The mixed chemistry is found in a variety of sources and this puts strong constraints on our current understanding of stellar evolution. The objects include PNe with very hot central stars NGC 6302; NGC 6537 (Molster et al. 2001a) where the C-rich PAH features are probably originating in the dissociation of CO by shocks; H-poor [WC] central stars of PNe (Waters et al. 1998a, Cohen et al. 1999), where the detection of both PAHs and cool O-rich circumstellar dust points to a very fast evolution from O- and H-rich to C-rich and H-poor, probably because of a late thermal pulse (Herwig et al. 1999) (see more in Section 6) and finally, also in previously considered canonical examples of post-AGB stars (e.g., the Red Rectangle) where there is evidence that the formation of a stable O-rich dust torus or disc antedated a more recent C-rich transition of the central object (Waters et al. 1998a). Because in the latter objects, binarity turns out to be a main ingredient in understanding these systems, I return to this item in Section 7. For some post-AGB stars with mixed chemistry like IRAS08005-2356 and Rob22 (e.g., Zijlstra et al. 2001), there is direct evidence for a dusty torus but binarity is only suspected.

5.3. Molecular Envelope

The molecular envelope around post-AGB stars is traditionally observed in the rotational lines at (sub-)mm and radio wavelengths but the rovibrational spectra of several species became also available at near and mid-IR wavelengths. For the carbon rich post-AGB stars, electronic transitions of circumstellar molecules are detected in the UV-optical spectra also (e.g., Hrivnak 1995, Bakker et al. 1997). Obviously, the molecular chemistry reflects the C/O dichotomy, except for the dominant CO and H_2. We witness the hardening of the radiation from the AGB to the PNe and, when the central star is hot enough to produce photodissociation radiation, atomic fine-structure lines become observable. This is typically when the central star becomes hotter than about 10000 K (Castro-Carrizo et al. 2001, Fong et al. 2001) indicating the PDR is mainly responsible for dissociation of the molecular envelope and not shocks. The hardening of the stellar radiation can also be inferred by the increased abundance of radicals and ion chemistry products CN, HNC, and HCO^+ in the AGB–post-AGB–PNe sequence (e.g., Bachiller et al. 1997).

Molecular hydrogen, the most abundant molecule, is not observed in AGB stars, but detected in post-AGB stars in the near-IR spectra by the rovibrational line S(1) $v = 1 \rightarrow 2$ at 2.122 μm. The emission in post-AGB stars is strongly linked with the bipolar nature of the post-AGB stars and the line is indicative of shocked regions. A good spatially resolved example is AFGL2688 (Sahai et al. 1998, see Section 5.1) where molecular hydrogen traces the shock front of the fast collimated outflows. Fluorescence excitation occurs only when the star is on the verge of ionizing the circumstellar shell (García-Hernández et al. 2002).

The abundant and stable CO can be traced in the whole envelope from close to the star to far out in the nebula and line-emission detections are used to trace both the kinematics and determine the mass-loss (history) of evolved stars by using the different components of the line-profile (e.g., Loup et al. 1993, Meixner et al. 1998, Bujarrabal et al. 2001). Moreover, rotational line emission of CO offers an important trace for the $^{12}C/^{13}C$ ratio, which is a very good indicator for the internal nucleosynthesis and dredge-up processes. Generally a ratio is found in the $\sim$10–25 range.

One of the main characteristics of mass-losing O-rich AGB stars is the maser emission, the most important of which are SiO, H_2O, and OH (in this order of spatial appearance from the central star outwards). The SiO and H_2O maser disappear fast after the cessation of the large amplitude pulsations and heavy mass-loss ending the AGB evolution (Nyman et al. 1998). The dying H_2O maser emission is even observed in OH17.7–2.0 (Engels 2002) on a timescale of only 10 years and also OH15.7+0.8 seems to be at the very beginning of its post-AGB evolution (Nyman et al. 1998, Engels 2002). OH masers persist longer and some PNe still have OH maser emission detections. OH masers in bipolar outflows were reviewed by Zijlstra et al. (2001) and, on top of the detection of high-velocity hubble-type flows, they also argue that the lifetime for the bipolar OH/IR stars in excess of 10^4 yr indicates a retarded post-AGB evolution and suggests that reaccretion on the star from the circumstellar dust may enhance the post-AGB lifetime considerably.

Circumstellar gas phase CO_2 is observed in the near IR of disc sources like the Red-Rectangle, (Waters et al. 1998a, Section 7) and HR 4049 (Cami & Yamamura 2001, Section 7).

C-rich post-AGB stars are richer in detected molecules, and the role of IRC+10216 in our understanding of the circumstellar chemistry around carbon stars is taken over by AFGL2688 and AFGL618 for post-AGB stars. In the latter, the UV photons of the hotter central star modify the chemistry considerably and recent discoveries, including C_4H_2, C_6H_2, and benzene (C_6H_6) (Cernicharo et al. 2001a,b) corroborate the finding that C-rich post-AGB stars are very efficient organic factories. In the inner small photodissociation region of AFGL618, O-rich species OH and H_2O were detected (Herpin & Cernicharo 2000). Also in the cooler AFGL2688, up to 20 molecular species were detected (Omont 2001).

In C-rich post-AGB stars, the famous bands at 3.3, 6.2, 7.7, 8.6, and 11.2 μm become excited, which is not the case on the AGB. These bands are historically called the Unidentified Infrared (UIR) bands. Many possible carriers were proposed (such that they are often called "Overidentified Infrared Bands"), but they are now generally attributed to the IR fluorescence of Polycyclic Aromatic Hydrocarbons molecules (PAHs). These PAHs are probably the most abundant complex carbon molecules in space (Tielens et al. 1999). Plateau emission features in the 6–9 and 11–17 μm region (Figures 1, 5) in post-AGB stars are associated with hydrocarbon features both aromatic and aliphatic (Kwok et al. 1999, 2001; Hony et al. 2003) with typically stronger aliphatic bonds in post-AGB stars than in the ensuing PNe spectra. The ISO spectroscopic results have allowed detailed studies of the many subfeatures and molecular complexes in all sources where these bands are observed (post-AGB stars, young stellar objects, H II regions, etc.) and allow detailed study of the environmental conditions of several bands, enabling study of the excitation, size, size distribution, and evolution of the PAHs (e.g., Hony et al. 2001, Van Kerckhoven et al. 2000). In only the enigmatic peculiar post-AGB star HR 4049 a 3.43 and 3.52 μm feature have been observed (Geballe et al. 1989, Molster et al. 1996) in addition to the PAH series (see Figure 5). These were identified as due to nanodiamonds (Guillois et al. 1999) and were found also in young stellar objects (Van Kerckhoven et al. 2002). HR 4049 is a strongly depleted binary (see Section 7) with a unique dust excess pointing to a peculiar disk: the dust can be very well fitted from about 1 μm all the way to 850 μm by a single black-body of 1150 K. This very much constrains the possible geometry and chemophysical characteristics of the disk, which must be gas-rich because of the large observed scale height (Dominik et al. 2003). Also, the chemical properties are very peculiar, not only because both O-rich and C-rich species are present but also because no chemical AGB model can explain the $^{16}O/^{17}O \sim 8.3 \pm 2.3$ and $^{16}O/^{18}O \sim 6.9 \pm 0.9$ deduced from CO_2 bands by Cami & Yamamura (2001). Although the presence of circumstellar diamonds is also found in another strongly depleted post-AGB star, HD 52961 (Oudmaijer et al. 1995), the presence of diamonds is certainly not common in C-rich post-AGB stars.

6. STELLAR EVOLUTION ON A HUMAN TIMESCALE: LATE THERMAL PULSES

The three famous examples of stellar evolution observed in "real time" associated with late thermal pulses are FG Sge, V 605 Aql, and Sakurai's object (V4334 Sgr). FG Sge was recorded on photographic plates in late 1880 to have a T_{eff} of about

43,000 K, while it was back near the AGB at about 5000 K in 1990, being still embedded in its old planetary nebula He 1–5 (van Genderen & Gautschy 1995). The visible magnitude increased by more than 4 magn. while the bolometric magnitude increased only slightly. Interestingly enough the chemical composition changed also, with s-process overabundances [up to Pb (Gonzales et al. 1998)] appearing prior to C-enhancement and even before the envelopes deepest convective penetration, while hydrogen stayed abundant (Blöcker & Schönberner 1997). Moreover, the star dropped some 4 magn. in 40 days due to dust obscuration, reminiscent of the typical drops of R CrB stars.

In the other two objects, the evolution was even faster: V 605 Aql brightened in 1919 and appeared as a $T_{eff} \sim 5000$ K star but was not monitored as well afterwards. It was rediscovered in the 1970s with the detection of the old PN, A58, with a central hydrogen deficient knot, probably originating from the 1919 event. The object is now faint but hot again and appears as a [WC] central star with $T_{eff} > 50{,}000$ K (Clayton & de Marco 1997).

The most recent example is Sakurai's object (after the Japanese amateur astronomer who discovered the brightening in 1996) or V4334 Sgr: it appeared as a eleventh magnitude star, stayed bright for only a few years when it dropped in magnitude from about eleventh to twenty-second in one year due to dust obscuration (Duerbeck et al. 2000). The prediscovery magnitude was $m_v = 15.5$ in 1994. Thanks to the recent event, a broad range of observational techniques has been used to monitor the rise and fall of this object (workshop edited by Evans & Smalley 2002). The chemical composition of V4334 Sgr changed in only a few months time with a decrease of H ($< +1.0$ dex) accompanied by an increase in Li ($>= 0.6$ dex) and light s-process abundances [A(Sr) > 0.7 dex] being the most noticeable (Asplund et al. 1999). Also the dust has been monitored and the optical decline is accompanied by an increase in IR flux due to the thermal radiation of graphite dust grains also indicating an increase in mass loss (Tyne et al. 2002).

The "born again" scenario's are expected to be very dependent on the remaining mass of the envelope: The fast evolution ending the blueward evolution can occur during the H-burning (late thermal pulse) or even during WD cooling track (very late thermal pulse), and the ensuing redwards evolution will occur typically on timescales shorter than the average astronomers career. Especially in the "very late thermal pulse" scenarios, the remaining H is consumed and virtually no H is left for the ensuing post-pulse evolution. Very late pulse scenarios are therefore the main channel to explain hydrogen deficient objects like the central stars of PNe with [WC] spectrum or the very hot hydrogen deficient PG1159 stars. The very fast evolution of Sakurai's object can, however, only be modeled with a modification in the mixing length efficiency of 100% downwards (Herwig 2001).

Objects often associated with these very late pulses are the R CrB stars (Section 1) and this link became even stronger after the discovery of the typical magnitude drops in the late-pulse trio mentioned above. Among the rare R CrB stars, the majority show abundances not understood in a late flash scenario to date, however. Detailed modeling is required because of the extreme abundances (C photoionization dominates the continuous opacity), but the C/He is probably not much larger than 1% (Asplund et al. 2000). Hydrogen deficiencies vary greatly and ranges from a factor of only 20 up to $>10^8$. s-process overabundances are found, and some objects display Li enrichment. The almost pure He content is not expected since the overshoot models predict mass ratios on the order of (He, C, O) = (40–50, 40–50, 5–10) (Herwig 2000). Note that among the four hot R CrB stars known to date (T_{eff} = 15,000–20,000 K), two (V348 Sgr and HV2671) do show these high C/He abundances but lack the high O abundance (De Marco et al. 2002). Two others are more similar to cool R CrB stars with almost pure He abundances. For one object (DY Cen) there is some evidence for binarity, which would make it the only R CrB star known to reside in a binary system to date (e.g., De Marco et al. 2002). V348 Sgr is embedded in a large extended PN which could classify the object as a PNe with a H-poor, C-rich [WC] central star.

The PNe with Wolf-Rayet central stars are other remarkable objects with hydrogen deficient C-rich central stars surrounded by PNe which do not differ significantly from mainstream PNe. They represent about 8% of the PNe population of our Galaxy (Górny 2001). The evolutionary history of these objects is not clear, certainly after the discovery of cool O-rich dust surrounding some of them (Waters et al. 1998a, Cohen et al. 1999). Several scenarios exist to explain the mixed chemistry (Cohen et al. 2002). An illustrative example is IRAS07027–7925, which is a PNe with a [WC] central star but with an OH maser from the relic O-rich mass-loss phase on the AGB: the transition time from O-rich (and H-rich) to C-rich (and H-poor) must have been smaller than the dynamical time of the OH-maser of some 500 yr (Zijlstra et al. 1991)! For CDP-56°8032 the presence of a dusty disc has been resolved, which may harbor the O-rich dust component (De Marco et al. 2002) similar to some binary post-AGB stars discussed below. The chemical composition of the central objects falls within the expected range concerning the He, C, and O abundances if diffusive overshoot is applied at the bottom of the convective He-tongue (Koesterke 2001). Similar abundances (although with a rather large intrinsic spread) are found in hydrogen deficient hot pre-WD stars (PG1159-stars) indicating a possible evolutionary link in which the PG1159 stars are descendents of the [WC]-objects (Werner 2001).

7. BINARIES AMONG POST-AGB STARS

Radial velocity measurements are still the main observational tool for finding binarity among a sample of stars. Because orbital periods expected for post-AGB stars that avoided spiral-in are rather large (one to several years), long monitoring campaigns are needed. Moreover, many objects are optically faint because of a combined effect of distance and (interstellar and circumstellar) reddening. Post-AGB stars are often intrinsically variable with considerable amplitudes yielding interpretation of variability in the radial velocity data as due to orbital motion and not straightforward. The observational bias is clearly toward optically bright objects without large amplitude pulsations.

Despite the constraints, many post-AGB stars in binaries were identified, and orbital elements could be deduced to such an extent that global observational characteristics of these systems can now be studied. In some objects, [e.g., HD 213985, F(M) = 0.95 $M_{\odot}$, Waelkens et al. (1987)] the high mass-function excludes a WD secondary but does imply strong mass-transfer. Most objects, if not all, are thought to possess unevolved companions.

7.1. e–log *P*

In Figure 6 we present the e– log *P* diagram of the post-AGB binaries and compare those to the diagram of Ba-stars taken from the compilation of Jorissen et al. (1998). The latter are also post-AGB stars in the sense that the current WD was once a mass-losing AGB star which, not only polluted (or enriched) the current Ba giant but also determined the orbital elements by dynamical interaction during its AGB phase. The same period spread is observed. For the post-AGB stars there is, however, a

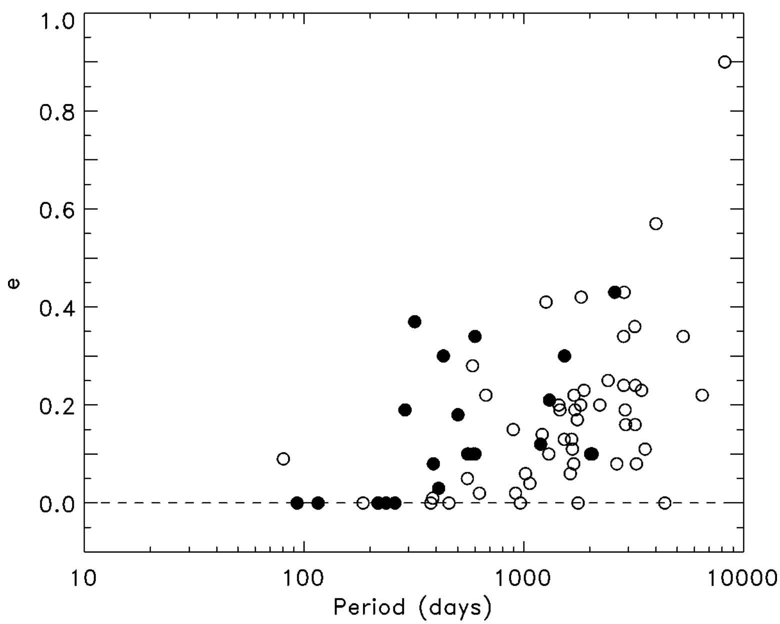

Figure 6 The e– log *P* diagram of post-AGB stars (*filled circles*). Data are from (Waters et al. 1993; Van Winckel et al. 1995, 1998, 1999; Pollard & Cottrell 1995; Gonzalez & Wallerstein 1996; Maas et al. 2002b; B.J. Hrivnak, private communication)]; supplemented with some unpublished orbits. The open circles are strong and mild Ba-giants from the compilation of Jorissen et al. (1998). The same periods are observed, only the post-AGB stars show an excess of eccentric orbits in the 200–600 days range. While for the long periods, the strong Ba sample is complete, this is not so for the post-AGB sample.

significant excess in eccentric orbits in the 200–600 days range compared to Ba stars. Also for Ba dwarfs and CH subgiants, there are a few systems within this period range with eccentric orbits.

Monte Carlo simulations have shown that systems of post-AGB stars with resulting periods on the order of one to a few hundred days can only be expected if an efficient mass-loss mechanism is induced to increase the mass-loss significantly prior to Roche-lobe overflow (RLOF), in order to decrease the envelope bining energy and to avoid severe spiral-in. The mass-loss enhancement parameter is critical in the models (Tout & Eggleton 1988; Han et al. 1995a,b), which are tuned to explain the e– $\log(P)$ diagrams of systems with a WD companion. A detailed set of simulations is presented in Karakas et al. (2000), including the effect of wind accretion, tidal interaction, (stable) RLOF, and enhanced mass loss, and the solution to explain the e– $\log P$ diagram of Ba stars does indeed need a significant mass-loss enhancement on the AGB compared to single stars evolutionary tracks. The period range and eccentricities of Ba stars could be recovered. More recent studies (Pols et al. 2003) are, however, at variance with these results and in their population synthesis computations, all systems with orbital periods of $P \geq 3000$ days are circularized by stable RLOF or tidal interation by the time the primary reaches its post-AGB phase of evolution. We conclude that the observed eccentric orbits (see Figure 6) of the post-AGB stars (and of the Ba stars) are not well understood but that the systems certainly did not evolve on single star evolutionary tracks and that binary interaction changed their evolution considerably.

Artymowicz et al. (1991) and Lubow & Artymowicz (1992) propose the tidal interaction with the circumstellar dusty disk can pump-up the eccentricity the same way young stellar binaries embedded in their natal cloud can be pumped up. Soker (2000) proposes a scenario with differential mass loss during the orbital period to prevent the tidal interaction to circularize the orbits.

Note that the depleted objects with known orbits are included in Figure 6, but nondepleted binaries exist as well: 89 Her, HD 95767, and EN Tra (HD 131356) being the most noticeable. Although the binary post-AGB stars are precursors of binaries with a WD companion and despite the similar orbital periods observed, it is unlikely that all the binary post-AGB stars discussed here are pre-Ba-stars since no s-process overabundances are observed! For depleted objects, it is difficult to trace s-process enrichment because these are refractory, but also the nondepleted objects are not s-process enhanced. Only for some objects, there is evidence for C-rich (and thus post third-dredge-up) material.

Observational evidence for enhanced mass loss in binary objects comes from SAO 173329, an F-star with a very short orbital period of 116 days and zero eccentricity, but with a strong P-Cygni H_α profile indicating a wind velocity of 300 km s^{-1} (Van Winckel et al. 2000). Similar P-Cygni profile is observed in the binary IRAS08544-4431 ($P_{orbit} = 502$ days, $e = 0.15$) by Maas et al. (2002a), where the velocity is modulated with the orbital period the maximal velocity being reached at upper conjunction. Because there is no evidence for a hot component in either system, the physical mechanism driving the very fast outflow is not known but likely linked to the rather close binary nature of the systems. Also in the enigmatic binary HD101584, a high velocity outflow reading 130 km s^{-1} was detected in CO (Trams et al. 1990).

7.2. SED + Binarity

The presence of hot dust ($T_{dust} \sim 1000$ K) in some post-AGB stars was first noticed by Trams et al. (1991) and interpreted as evidence for significant post-AGB mass loss. As more and more systems became known, this interpretation became untenable: a dusty post-AGB mass loss would speed-up the evolution such that very few objects would be observable (Trams et al. 1989). Detailed radial velocity monitoring campaigns learned that the systems with hot dust are binaries and all but two systems displayed in Figure 6 are indeed binaries with a hot dust component, in which the dust remains longer in the immediate surroundings of the star instead of freely expanding. In a homogeneous radial velocity monitoring program of objects with broad IR excesses, Maas et al. (2002b) reports the detection of a high fraction of binaries and five orbit determinations. The final statistics of that program are not yet available. On the other hand, Hrivnak & Lu (2000) report on the radial velocity monitoring of nine post-AGB stars with double-peaked SED and in none of them, was orbital motion detected.

The geometry of the dust in some of these binaries is constrained by circumstellar extinction measurements varying in phase with orbital motion [HR 4049, (Waelkens et al. 1996); HD 213985, (Waelkens et al. 1995); U Mon, (Pollard & Cottrell 1995)] or by spectropolarimetric observations (Johnson et al. 1999).

There is growing observational evidence that the dusty flattened geometries around these binaries are remarkably stable. To illustrate the impact of binarity on the observational characteristics of the objects, the next subsection focuses on two case studies.

7.3. Case Studies of Binary Stars: Red Rectangle and AC Her

The Red Rectangle (RR), with the central HD 44179, is a famous C-rich bipolar nebula discovered by (Cohen et al. 1975) that displays remarkable phenomena in a very wide wavelength domain. It is often used as an archetypical example of a C-rich post-AGB stars but it is clear that many characteristics are intimately related to the nature of the central binary [$P_{orbit} = 318$ days, $e = 0.37$, Waelkens et al. (1996)]. The central star is not seen in direct light but is obscured by an optically and geometrically thick disc (Roddier et al. 1995, Osterbart et al. 1997, Bond 1997). Recent constraints from SED modeling by Men'shckikov et al. (2002) give a distance of 710 pc. The optical photometric variability is gray and varies in phase with orbital motion, which is probably due to the variation of scattering angle during orbital motion (Waelkens et al. 1996). The pristine metallicity is not known because the object is severely depleted. The C-rich nebula is best known for its strong PAH bands in the near and mid-IR (Russell et al. 1978), and also for its strong extended red emission (ERE), seen only in C-rich environments (Furton & Witt 1992) and which was recently attributed to crystalline silicon nanoparticles (Witt et al. 1998, Ledoux et al. 1998). (Li & Draine 2002) argue that this can only be true if attached to larger grains or clustered. The panoply of emission lines on top of the ERE emission (Schmidt et al. 1980) remain unidentified but the centra and full width half maximum (FWHM) of some features decrease with increasing distance from the central object and converge to some narrow diffuse interstellar bands (DIBs) (Sarre et al. 1995, Van Winckel et al. 2002). The DIB analogy was questioned, however (Glinski & Anderson 2002). The presence of CH^+ lines (Balm & Jura 1992) corroborated the C-rich nature of the nebula. In recent modeling inspired by *HST* images, (Icke 2002) models very similar structures by a spherical symmetric intermittent wind, which is focused by an oblique shock and creates biconal structures.

The extremely narrow, weak microwave CO emission observed in the RR (Jura et al. 1995) and the presence of large grains (Jura et al. 1997) are distinct characteristics best explained by the long-term processing of dust in a circumbinary keplerian disc. This was confirmed by the detection of O-rich crystalline silicates in the mid-infrared ISO spectrum (Waters et al. 1998a). The most likely scenario for O-rich material in this C-rich environment is that the formation of the O-rich disc antedated a recent C-rich phase of HD 44179 during which the nebula was expelled. Also O-rich gas phase material was found in the form of circumstellar CO_2 (Waters et al. 1998a) and electronic transitions of OH (Reese & Sitko 1996). The dynamical age of the nebula is not less than 2 10^4 years (assuming a distance of 710 pc and an outflow velocity of 10 km s^{-1}).

AC Her is a RV Tau star that is known for its regularity in the light curve (Zsoldos 1993). It is a binary with a period of 1200 days (Van Winckel et al. 1998) and a strongly depleted photosphere (Giridhar et al. 1998, Van Winckel et al. 1998). The dusty disc is resolved in the mid-IR by Jura et al. (2000) and also there is a weak narrow CO rotational line emission (Bujarrabal et al. 1988) pointing to keplerian rotation instead of expansion (Jura et al. 1995). Dust particles in the system are large revealing strongly processed dust characteristics (Molster et al. 2002b) typical of disc sources with most noticeably a very similar 10 μm silicate band than in the solar system comet Hale-Bopp. RV Tau stars in general are known to be poor CO emitters (Bujarrabal et al. 1988, Alcolea & Bujarrabal 1991), this together with the chemical information and the dust characteristics led Van Winckel et al. (1999) to conclude that binarity may be a widespread phenomenon among RV Tau stars. The main difference between RV Tau stars with and without mean magnitude variations, would then be a difference of projection of the circumstellar material in the plane of the sky. Note that the RV Tau stars follow a P-L relation, which is the natural high-luminosity end of the W Vir pop II Cepheid instability strip. This would indicate that the dynamical influence of the companion alters the mass-loss history such that objects evolve through the instability strip or reside there for a longer time.

7.4. Binary Evolution

The most important common characteristic of the binary post-AGB stars seems to be that (part of the) circumstellar material is trapped in a remarkably stable circumbinary (or circumstellar) geometry. The orbits, determined till now, span the range from a few hundred up to 2100 days and the objects in the shorter orbits certainly did not evolve on single-star evolutionary tracks.

Dusty tori are detected in more objects than the confirmed binaries (see Section 5.3). If reaccretion of matter from such a stable torus equals the nuclear burning rate (typically $10^{-7}\ M_{\odot}\ \mathrm{yr}^{-1}$) the evolution will slow down significantly, making these objects more likely to be discovered. This may also explain the high occurrence of bipolar outflows among the post-AGB stars (Zijlstra et al. 2001).

Interesting analogues of mixed chemistry post-AGB stars are found in the enigmatic J-type carbon stars. The O-rich circumstellar dust, which is observed in 5–10% of these objects (Lloyd Evans 1991) is also best explained in a binary evolution context (Little-Marenin 1986, Evans 1990) in which this dust is trapped in a binary system. Additional weak and narrow CO measurements pointed to a long-lived reservoir of gravitationally bound gas (Jura & Kahane 1999), and in a recent scenario proposed by Yamamura et al. (2000) on the basis of their analysis of ISO-SWS spectra, these objects are wide binaries in which the dust is stored around the unseen companion. In none of these systems are high amplitude radial velocity variations detected implying rather large orbits (Barnbaum et al. 1991). Also the object with the largest crystallinity silicate fraction is a J-type carbon stars IRAS09425-6040 (Molster et al. 2001a). Whether the special chemical composition of the J-type carbon stars (no s-process overabundances, small $^{12}C/^{13}C$ ratio) is linked to the proposed binarity in wide systems remains an open question.

The actual confirmed binary sample is strongly biased toward relatively bright objects, but whereas the dust, trapped in a (circumbinary) reservoir, remains detectable on a much longer timescale, post-AGB samples based on IR measurements of the thermal radiation of dust are bound to be biased toward binaries. Moreover, the future evolution of the nebula, especially in the PNe phase, will be determined by the high pole-to-equator gradient in the circumstellar environment.

8. CONCLUSION

In this review an overview is presented on the broad characteristics of post-AGB objects. Because the evolution is fast and covers a broad range of stellar temperatures, a complete picture of all facets of the fast evolutionary phase from the late AGB to the PNe is beyond our current understanding, the more so because several individual “prototypical” objects turned out to have evolved on nonstandard AGB tracks. The versatile influence of a companion affects the observational characteristics of the object and binarity may bias many samples. Observational (and personal) biases are therefore certainly present in the selection of topics included.

As stated earlier, no complete statistical selection of objects is yet possible and detailed study of individual objects prevail, making putative evolutionary links between individual objects tempting but often based on incomplete understanding of the objects. The main problem is our poor knowledge of the luminosities. Moreover, extensive monitoring campaigns are needed to test the central stars on binarity.

Yet it is clear that the diverse spectral signatures of post-AGB stars are rich in diagnostics, not only to study the post-AGB evolution itself, but also to constrain (nucleosynthetic) AGB evolution. Moreover, the key ingredients to understanding the morphological variety of PNe are being developed during the post-AGB evolution, and a good understanding of the physical processes involved are fundamental in understanding how the stellar outflows develop.

New insights are often triggered by new observing facilities and in the (near) future both ground-based and space-born infrastructures are bound to give new impetus on the subject. Recent efficient optical spectrographs on 10 m class telescopes are enabling us to probe the (chemical) characteristics of faint central objects, even with high-resolution. The spatial distribution of the circumstellar dust is clearly important and in the near future new powerful (interferometric) instruments mounted on large telescopes will enable us to resolve in unprecedented spatial resolution the circumstellar geometry, a requisite to understanding the onset of bipolarity. Spatially resolved cool dust components probing the story of the mass-loss history will be possible with the bolometer arrays planned both from the ground and in space. Despite the poor resolution, parsec-sized dust envelopes were resolved by ISO around the IR-bright AFGL 2688 and AFGL 618 indicating a rich potential for Hershel and ALMA. The rich solid-state spectra of post-AGB stars contribute to our understanding of the young rapidly evolving research area of circumstellar mineralogy. Although the legacy of ISO is far from being harvested completely, the increase in sensitivity of SIRTF will certainly foster new insights and contribute to our understanding of the characteristics of the dust being fed to the ISM, while the IR-survey of ASTRO-F will yield a bigger sample of post-AGB stars. During the transition, the hardening of the stellar radiation is witnessed in the molecular chemistry and our current understanding on the chemical and dynamical circumstellar processes are heavily based on detailed observations of only a few objects. New (sub)mm interferometric projects like ALMA will certainly profoundly effect this field, together with the infrared spectrometer on NGST and the heterodyne instrument on the Hershel mission.

Although inaccurate luminosity determinations of field post-AGB stars are likely to linger until the launch of accurate astrometric satellites like GAIA, the prospects for significant progress in the near future in our understanding of the late stages of stellar evolution are very good.

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LITERATURE CITED

Abia C, Busso M, Gallino R, Domínguez I, Straniero O, Isern J. 2001. *Ap. J.* 559:1117

Abia C, Wallerstein G. 1998. *MNRAS* 293: 89

Alcock C, Allsman RA, Alves DR, Axelrod TS, Becker A, et al. 1998. *Astron. J.* 115:1921

Alcock C, Allsman RA, Alves DR, Axelrod TS, Becker A, et al. 2001. *Ap. J.* 554:298

Alcolea J, Bujarrabal V. 1991. *Astron. Astrophys.* 245:499

Alves DR, Bond HE, Onken C. 2001. *Astron. J.* 121:318

Artymowicz P, Clarke CJ, Lubow SH, Pringle JE. 1991. *Ap. J.* 370:L35

Asplund M, Gustafsson B, Lambert DL, Rao NK. 2000. *Astron. Astrophys.* 353:287

Asplund M, Lambert DL, Kipper T, Pollacco D, Shetrone MD. 1999. *Astron. Astrophys.* 343:507

Bachiller R, Forveille T, Huggins PJ, Cox P. 1997. *Astron. Astrophys.* 324:1123

Bakker EJ, Lambert DL. 1998. *Ap. J.* 508:387

Bakker EJ, van Dishoeck EF, Waters LBFM, Schoenmaker T. 1997. *Astron. Astrophys.* 323:469

Balick B, Frank A. 2002. *Annu. Rev. Astron. Astrophys.* 40:439

Balick B, Wilson J, Hajian AR. 2001. *Astron. J.* 121:354

Balm SP, Jura M. 1992. *Astron. Astrophys.* 261: L25

Barlow MJ. 1998. *Astrophys. Space Sci.* 255: 315

Barnbaum C, Kastner JH, Morris M, Likkel L. 1991. *Astron. Astrophys.* 251:79

Bernatowicz TJ, Cowsik R, Gibbons PC, Lodders K, Fegley BJ, et al. 1996. *Ap. J.* 472: 760

Bidelman WP. 1951. *Ap. J.* 113:304

Biémont E, Palmeri P, Quinet P. 1999. *Astrophys. Space Sci.* 269:635

Blöcker T. 2001. *Astrophys. Space Sci.* 275:1

Blöcker T. 1995. *Astron. Astrophys.* 299:755

Blöcker T, Schönberner D. 1997. *Astron. Astrophys.* 324:991

Bond HE. 1991. In *IAU Symp. 145: Evolution of Stars: the Photospheric Abundance Connection*, ed. G Michaud, A Tutukov, p. 341/ Dordrecht: Kluwer

Bond HE. 1997. In *IAU Symp. 180: Planetary Nebulae*, ed. HI Habing, HJGLM Lamers, p. 460. Dordrecht: Kluwer

Bond HE, Alves DR. 2001. See Szczerba & Górny 2001, p. 77

Bond HE, Luck RE. 1987. *Ap. J.* 312:203

Bujarrabal V, Alcolea J, Planesas P. 1992. *Astron. Astrophys.* 257:701

Bujarrabal V, Bachiller R, Alcolea J, Martin-Pintado J. 1988. *Astron. Astrophys.* 206: L17

Bujarrabal V, Castro-Carrizo A, Alcolea J, Sánchez Contreras C. 2001. *Astron. Astrophys.* 377:868

Busso M, Gallino R, Lambert DL, Travaglio C, Smith VV. 2001. *Ap. J.* 557:802

Busso M, Gallino R, Wasserburg GJ. 1999. *Annu. Rev. Astron. Astrophys.* 37:239

Cami J, Yamamura I. 2001. *Astron. Astrophys.* 367:L1

Castro-Carrizo A, Bujarrabal V, Fong D, Meixner M, Tielens AGGM, et al. 2001. *Astron. Astrophys.* 367:674

Cernicharo J, Heras AM, Pardo JR, Tielens AGGM, Guélin M, et al. 2001a. *Ap. J.* 546: L127
Cernicharo J, Heras AM, Tielens AGGM, Pardo JR, Herpin F, et al. 2001b. *Ap. J.* 546:L123
Clayton GC. 1996. *Publ. Astron. Soc. Pac.* 108: 225
Clayton GC, de Marco O. 1997. *Astron. J.* 114: 2679
Cohen M, Anderson CM, Cowley A, Coyne GV, Fawley W, et al. 1975. *Ap. J.* 196:179
Cohen M, Barlow MJ, Liu X-W, Jones AF. 2002. *MNRAS* 332:879
Cohen M, Barlow MJ, Sylvester RJ, Liu X-W, Cox P, et al. 1999. *Ap. J. Lett.* 513:L135
Conlon ES, Dufton PL, Keenan FP. 1994. *Astron. Astrophys.* 290:897
Conlon ES, Dufton PL, Keenan FP, McCausland RJH, Little JE. 1993a. *Astron. Astrophys.* 272:243
Conlon ES, Dufton PL, McCausland RJH, Keenan FP. 1993b. *Ap. J.* 408:593
Corradi RLM, Schwarz HE. 1995. *Astron. Astrophys.* 293:871
Cox P, Lucas R, Huggins PJ, Forveille T, Bachiller R, et al. 2000. *Astron. Astrophys.* 353:L25
de Marco O, Clayton GC, Herwig F, Pollacco DL, Clark JS, Kilkenny D. 2002. *Astron. J.* 123:3387
Dominik C, Dullenmond CP, Cami J, Van Winckel H. 2003. *Astron. Astrophys.* 397:595
Duerbeck HW, Liller W, Sterken C, Benetti S, van Genderen AM, et al. 2000. *Astron. J.* 119:2360
Engels D. 2002. *Astron. Astrophys.* 388:252
Evans A, Smalley B. 2002. *Astrophys. Space Sci.* 279:5
Evans TL. 1985. *MNRAS* 217:493
Evans TL. 1990. *MNRAS* 243:336
Fong D, Meixner M, Castro-Carrizo A, Bujarrabal V, Latter WB, et al. 2001. *Astron. Astrophys.* 367:652
Forrest WJ, Houck JR, McCarthy JF. 1981. *Ap. J.* 248:195
Forveille T, Morris M, Omont A, Likkel L. 1987. *Astron. Astrophys.* 176:L13
Frost CA, Lattanzio JC. 1996. *Ap. J.* 473:383
Furton DG, Witt AN. 1992. *Ap. J.* 386:587
García-Hernández DA, Manchado A, García-Lario P, Domínguez-Tagle C, Conway GM, Prada F. 2002. *Astron. Astrophys.* 387: 955
García-Lario P, Manchado A, Pyck W, Pottasch SR. 1997. *Astron. Astrophys. Suppl.* 126: 479
García-Lario P, Manchado A, Ulla A, Manteiga M. 1999. *Ap. J.* 513:941
Geballe TR, Noll KS, Whittet DCB, Waters LBFM. 1989. *Ap. J. Lett.* 340:L29
Gehrz RD. 1972. *Ap. J.* 178:715
Giridhar S, Lambert DL, Gonzalez G. 1998. *Ap. J.* 509:366
Giridhar S, Lambert DL, Gonzalez G. 2000. *Ap. J.* 531:521
Giridhar S, Rao NK, Lambert DL. 1994. *Ap. J.* 437:476
Gledhill TM, Yates JA, Richards AMS. 2001. *MNRAS* 328:301
Glinski RJ, Anderson CM. 2002. *MNRAS* 332: L17
Goebel JH, Moseley SH. 1985. *Ap. J.* 290: L35
Gonzalez G, Lambert DL, Giridhar S. 1997a. *Ap. J.* 481:452
Gonzalez G, Lambert DL, Giridhar S. 1997b. *Ap. J.* 479:427
Gonzalez G, Wallerstein G. 1994. *Astron. J.* 108:1325
Gonzalez G, Wallerstein G. 1996. *MNRAS* 280: 515
Gonzalez G, Lambert DL, Wallerstein G, Rao HK, Smith V, McCarthy JK. 1998. *Ap. J. Suppl.* 114:133
Goriely S, Mowlavi N. 2000. *Astron. Astrophys.* 362:599
Górny SK. 2001. *Astrophys. Space Sci.* 275:67
Groenewegen MAT. 1999. See Le Bertre et al. 1999, p. 535
Groenewegen MAT, van den Hoek LB, de Jong T. 1995. *Astron. Astrophys.* 293:381
Guillois O, Ledoux G, Reynaud C. 1999. *Ap. J. Lett.* 521:L133
Habing HJ, van der Veen W, Geballe T. 1987. In *Late Stages of Stellar Evolution*, Calgary, p. 91. Dordreckt: D. Reidel

Han Z, Eggleton PP, Podsiadlowski P, Tout CA. 1995a. *MNRAS* 277:1443
Han Z, Podsiadlowski P, Eggleton PP. 1995b. *MNRAS* 272:800
Hawkins GW, Skinner CJ, Meixner MM, Jernigan JG, Arens JF, et al. 1995. *Ap. J.* 452: 314
Herpin F, Cernicharo J. 2000. *Ap. J. Lett.* 530:L129
Herwig F. 2000. *Astron. Astrophys.* 360:952
Herwig F. 2001. *Ap. J. Lett.* 554:L71
Herwig F, Blöcker T, Langer N, Driebe T. 1999. *Astron. Astrophys.* 349:L5
Herwig F, Blöcker T, Schönberner D, El Eid M. 1997. *Astron. Astrophys.* 324:L81
Herwig F, Langer N, Lugaro M. 2003. *Ap. J.* In press
Hony S, Tielens AGGM, Waters LBFM, de Koter A. 2003. *Astron. Astrophys.* 402:211
Hony S, Waters LBFM, Tielens AGGM. 2001. *Astron. Astrophys.* 378:L41
Hony S, Waters LBFM, Tielens AGGM. 2002. *Astron. Astrophys.* 390:533
Hoogzaad SN, Molster FJ, Dominik C, Waters LBFM, Barlow MJ, de Koter A. 2002. *Astron. Astrophys.* 389:547
Hrivnak BJ. 1995. *Ap. J.* 438:341
Hrivnak BJ, Kwok S, Su KYL. 2001. *Astron. J.* 121:2775
Hrivnak BJ, Kwok S, Volk KM. 1989. *Ap. J.* 346:265
Hrivnak BJ, Lu W. 2000. In *IAU Symp. 177: The Carbon Star Phenomenon*, ed. RF Wing, p. 293. Dordrecht: Kluwer
Hu JY, Slijkhuis S, de Jong T, Jiang BW. 1993. *Astron. Astrophys. Suppl.* 100:413
Iben I. 1984. *Ap. J.* 277:333
Iben I, Renzini A. 1983. *Annu. Rev. Astron. Astrophys.* 21:271
Icke V. 2002. In *PNe, Their Evolution and Role in the Universe*, ed. S Kwok, M Dopita, R Sutherland. *ASP Conf. Ser. 209*, San Francisco: Astron. Soc. Pac.
Johnson JJ, Anderson CM, Bjorkman KS, Code AD, Fox GK, et al. 1999. *MNRAS* 306: 531
Jorissen A, Van Eck S, Mayor M, Udry S. 1998. *Astron. Astrophys.* 332:877
Josselin E, Lèbre A. 2001. *Astron. Astrophys.* 367:826
Jura M. 1986. *Ap. J.* 309:732
Jura M, Balm SP, Kahane C. 1995. *Ap. J.* 453:721
Jura M, Kahane C. 1999. *Ap. J.* 521:302
Jura M, Turner J, Balm SP. 1997. *Ap. J.* 474:741
Jura M, Turner JL, Van Dyk S, Knapp GR. 2000. *Ap. J.* 528:L105
Jura M, Velusamy T, Werner MW. 2001. *Ap. J.* 556:408
Karakas AI, Tout CA, Lattanzio JC. 2000. *MNRAS* 316:689
Kastner JH, Weintraub DA. 1995. *Ap. J.* 452: 833
Kendall TR, Brown PJF, Conlon ES, Dufton PL, Keenan FP. 1994. *Astron. Astrophys.* 291: 851
Kipper T. 1998. *Baltic Astron.* 7:435
Klochkova VG. 1995. *MNRAS* 272:710
Koesterke L. 2001. *Astrophys. Space Sci.* 275: 41
Kupka F, Piskunov N, Ryabchikova TA, Stempels HC, Weiss WW. 1999. *Astron. Astrophys. Suppl.* 138:119
Kwok S. 1993. *Annu. Rev. Astron. Astrophys.* 31:63
Kwok S, Boreiko RT, Hrivnak BJ. 1987. *Ap. J.* 312:303
Kwok S, Hrivnak BJ, Su KYL. 2000. *Ap. J. Lett.* 544:L149
Kwok S, Volk K, Bernath P. 2001. *Ap. J. Lett.* 554:L87
Kwok S, Volk K, Hrivnak BJ. 1999. *Astron. Astrophys.* 350:L35
Kwok S, Volk KM, Hrivnak BJ. 1989. *Ap. J. Lett.* 345:L51
Lambert DL, Hinkle KH, Luck RE. 1988. *Ap. J.* 333:917
Lambert DL, Smith VV, Busso M, Gallino R, Straniero O. 1995. *Ap. J.* 450:302
Langer N, Heger A, Wellstein S, Herwig F. 1999. *Astron. Astrophys.* 346:L37
Lattanzio J, Forestini M. 1999. See Le Bertre et al. 1999, p. 31
Le Bertre T, Lébre A, Waelkens C, eds. 1999. *IAU Symp. 191: Asymptotic Giant Branch Stars*, San Francisco: Astron. Soc. Pac.

Ledoux G, Ehbrecht M, Guillois O, Huisken F, Kohn B, et al. 1998. *Astron. Astrophys.* 333:L39

Li A, Draine BT. 2002. *Ap. J.* 564:803

Little-Marenin IR. 1986. *Ap. J. Lett.* 307: L15

Lloyd Evans T. 1991. *MNRAS* 249:409

Lodders K, Fegley B. 1998. *The Planetary Scientist's Companion*. New York: Oxford Univ. Press

Loup C, Forveille T, Omont A, Paul JF. 1993. *Astron. Astrophys. Suppl.* 99:291

Lubow SH, Artymowicz P. 1992. In *Binaries as Tracers of Stellar Formation. Proc. Workshop held in Bettmeralp, Switz., Sept. 1991, in honor of Dr. Roger Griffin*, ed. A Duquennoy, M Mayor. Cambridge, UK: Cambridge Univ. Press

Luck RE, Bond HE, Lambert DL. 1990. *Ap. J.* 357:188

Lugaro RM, Herwig F, Lattanzio JC, Gallius R, Straniero O. 2003. *Ap. J.* 536:188

Maas T, Van Winckel H, Lloyd Evans T. 2002a. In *ASP Conf. Ser. XX: Symbiotic Stars Probing Stellar Evolution*, ed. R Corradi, J Mikolajewska, TH Mahoney. San Francisco: Publ. Astron. Soc. Pac. In press

Maas T, Van Winckel H, Waelkens C. 2002b. *Astron. Astrophys.* 586:1305

Manchado A, Garcia-Lario P, Esteban C, Mampaso A, Pottasch SR. 1989. *Astron. Astrophys.* 214:139

Marigo P, Girardi L, Bressan A. 1999. *Astron. Astrophys.* 344:123

Mathis JS, Lamers HJGLM. 1992. *Astron. Astrophys.* 259:L39

McCausland RJH, Conlon ES, Dufton PL, Keenan FP. 1992. *Ap. J.* 394:298

Meixner M, Campbell MT, Welch WJ, Likkel L. 1998. *Ap. J.* 509:392

Meixner M, Skinner CJ, Graham JR, Keto E, Jernigan JG, Arens JF. 1997. *Ap. J.* 482: 897

Meixner M, Ueta T, Bobrowsky M, Speck A. 2002. *Ap. J.* 571:936

Meixner M, Ueta T, Dayal A, Hora JL, Fazio G, et al. 1999. *Ap. J. Suppl.* 122:221

Men'shchikov AB, Schertl D, Tuthill PG, Weigelt G, Yungeslon LR. 2002. *Astron. Astrophys.* 393:867–85

Merrill P. 1952. *Science* 115:484

Moehler S. 2001. *Publ. Astron. Soc. Pac.* 113: 1162

Moehler S, Heber U. 1998. *Astron. Astrophys.* 335:985

Moehler S, Heber U, Lemke M, Napiwotzki R. 1998. *Astron. Astrophys.* 339:537

Molster FJ, Lim TL, Sylvester RJ, Waters LBFM, Barlow MJ, et al. 2001a. *Astron. Astrophys.* 372:165

Molster FJ, van den Ancker ME, Tielens AGGM, Waters LBFM, Beintema DA, et al. 1996. *Astron. Astrophys.* 315:L373

Molster FJ, Waters LBFM, Tielens AGGM. 2002a. *Astron. Astrophys.* 382:222

Molster FJ, Waters LBFM, Tielens AGGM, Barlow MJ, 2002b. *Astron. Astrophys.* 382: 184

Molster FJ, Waters LBFM, Tielens AGGM, Koike C, Chihara H. 2002c. *Astron. Astrophys.* 382:241

Molster FJ, Yamamura I, Waters LBF, Nyman L, Käufl H, et al. 2001b. *Astron. Astrophys.* 366:923

Molster FJ, Yamamura I, Waters LBFM, Tielens AGGM, de Graauw T, et al. 1999. *Nature* 401:563

Mooney CJ, Rolleston WRJ, Keenan FP, Dufton PL, Pollacco DL, Magee HR. 2001. *MNRAS* 326:1101

Mowlavi N. 1999. *Astron. Astrophys.* 344:617

Napiwotzki R, Heber U, Koeppen J. 1994. *Astron. Astrophys.* 292:239

Napiwotzki R, Herrmann M, Heber U, Altmann M. 2001. See Szczerba & Górny 2001, p. 277

Ney EP, Merrill KM, Becklin EE, Neugebauer G, Wynn-Williams CG. 1975. *Ap. J.* 198:L129

Nyman L-A, Hall PJ, Olofsson H. 1998. *Astron. Astrophys. Suppl.* 127:185

Omont A. 2001. See Szczerba & Górny 2001, p. 357

Osterbart R, Langer N, Weigelt G. 1997. *Astron. Astrophys.* 325:609

Oudmaijer RD, van der Veen WECJ, Waters

LBFM, Trams NR, Waelkens C, Engelsman E. 1992. *Astron. Astrophys. Suppl.* 96:625
Oudmaijer RD, Waters LBFM, van der Veen WECJ, Geballe TR. 1995. *Astron. Astrophys.* 299:69
Paczyński B. 1970. *Acta Astron.* 20:47
Parthasarathy M, Gauba G, Fujii T, Nakada Y. 2001. See Szczerba & Górny 2001, p. 29
Plez B, Smith VV, Lambert DL. 1993. *Ap. J.* 418:812
Pollard KH, Cottrell PL. 1995. In *ASP Conf. Ser. 83: IAU Colloq. 155: Astrophysical Applications of Stellar Pulsation*, p. 409. San Francisco: Publ. Astron. Soc. Pac.
Pols OR, Karakas AI, Lattanzio JC, Tout CA. 2003. In *ASP Conf. Ser.: Symbiotic Stars Probing Stellar Evolution*, ed. R Corradi, J Mikolajewska, TJ Mahoney. San Francisco: Publ. Astron. Soc. Pac. In press
Pottasch SR, Parthasarathy M. 1988. *Astron. Astrophys.* 192:182
Preston GW, Krzeminski W, Smak J, Williams JA. 1963. *Ap. J.* 137:401
Reddy BE, Bakker EJ, Hrivnak BJ. 1999. *Ap. J.* 524:831
Reddy BE, Lambert DL, Gonzalez G, Yong D. 2002. *Ap. J.* 564:482
Reese MD, Sitko ML. 1996. *Ap. J. Lett.* 467: L105
Reyniers M. 2002. *High resolution spectroscopy of post-AGB stars: AGB nucleosynthesis and dredge-up*. PhD thesis. KU Leuven, Belgium. 223 pp.
Reyniers M, Van Winckel H. 2001. *Astron. Astrophys.* 365:465
Reyniers M, Van Winckel H, Biemont E, Quimet P. 2002. *Astron. Astrophys.* 395: L35
Roddier F, Roddier C, Graves JE, Northcott MJ. 1995. *Ap. J.* 443:249
Russell RW, Soifer BT, Willner SP. 1978. *Ap. J.* 220:568
Sahai R. 1999. *Ap. J. Lett.* 524:L125
Sahai R. 2001. See Szczerba & Górny 2001, p. 53
Sahai R, Hines DC, Kastner JH, Weintraub DA, Trauger JT, et al. 1998. *Ap. J. Lett.* 492: L163
Sánchez Contreras C, Sahai R. 2001. *Ap. J. Lett.* 553:L173
Sarre PJ, Miles JR, Scarrott SM. 1995. *Science* 269:674
Schmidt GD, Cohen M, Margon B. 1980. *Ap. J. Lett.* 239:L133
Schönberner D. 1979. *Astron. Astrophys.* 79:108
Schönberner D. 1983. *Ap. J.* 272:708
Schönberner D. 1997. In *IAU Symp. 180: Planetary Nebulae*, ed. HJ Habing, HJGLM Lamers, p. 379. Dordrecht: Kluwer
Simis YJW, Icke V, Dominik C. 2001. *Astron. Astrophys.* 371:205
Smith VV, Lambert DL. 1989. *Ap. J. Lett.* 345:L75
Smith VV, Lambert DL. 1990. *Ap. J. Suppl.* 72:387
Soker N. 2000. *Astron. Astrophys.* 357:557
Soker N. 2002. *Ap. J.* 570:369
Speck AK, Meixner M, Knapp GR. 2000. *Ap. J. Lett.* 545:L145
Straniero O, Chieffi A, Limongi M, Busso M, Gallino R, Arlandini C. 1997. *Ap. J. Lett.* 478:332
Straniero O, Gallino R, Busso M, Chiefei A, Raiteri CM, et al. 1995. *Ap. J.* 440:L85
Su KYL, Hrivnak BJ, Kwok S. 2001. *Astron. J.* 122:1525
Sylvester RJ, Kemper F, Barlow MJ, de Jong T, Waters LBFM, et al. 1999. *Astron. Astrophys.* 352:587
Szczerba R, Górny SK, eds. 2001. *Post-AGB Objects as a Phase of Stellar Evolution*, Dordrecht: Kluwer. 448 pp.
Szczerba R, Górny SK, Zalfresso-Jundziłło M. 2001. See Szczerba & Górny 2001, p. 13
Takada-Hidai M. 1990. *Publ. Astron. Soc. Pac.* 102:139
Thévenin F, Parthasarathy M, Jasniewicz G. 2000. *Astron. Astrophys.* 359:138
Tielens AGGM, Hony S, van Kerckhoven C, Peeters E. 1999. In *ESA SP-427: The Universe as Seen by ISO*, ed. P Cox, MF Kessler, 427:579. Noordwijk, Neth: ESA
Tout CA, Eggleton PP. 1988. *MNRAS* 231: 823
Trams NR, Lamers HJGLM, van der Veen

WECJ, Waelkens C, Waters LBFM. 1990. *Astron. Astrophys.* 233:153
Trams NR, Waters LBFM, Lamers HJGLM, Waelkens C, Geballe TR, The PS. 1991. *Astron. Astrophys. Suppl.* 87:361
Trams NR, Waters LBFM, Waelkens C, Lamers HJGLM, van der Veen WECJ. 1989. *Astron. Astrophys.* 218:L1
Tyne VH, Evans A, Geballe TR, Eyres SPS, Smalley B, Duerbeck HW. 2002. *MNRAS* 334:875
Ueta T, Meixner M, Bobrowsky M. 2000. *Ap. J.* 528:861
Utsumi K. 1985. In *ASSL Cool Stars with Excesses of Heavy Elements*, Dordrecht: D. Reidel. 114:243
van der Veen WECJ, Habing HJ, Geballe TR. 1989. *Astron. Astrophys.* 226:108
Van de Steene GC, van Hoof PAM, Wood PR. 2000. *Astron. Astrophys.* 362:984
Van Eck S, Goriely S, Jorissen A, Plez B. 2001. *Nature* 412:793
Van Eck S, Goriely S, Jorissen A, Plez B. 2003. *Astron. Astrophys.* In press
van Genderen AM, Gautschy A. 1995. *Astron. Astrophys.* 294:453
Van Kerckhoven C, Hony S, Peeters E, Tielens AGGM, Allamandola LJ, et al. 2000. *Astron. Astrophys.* 357:1013
Van Kerckhoven C, Tielens AGGM, Waelkens C. 2002. *Astron. Astrophys.* 384:568
Van Winckel H. 1997. *Astron. Astrophys.* 319:561
Van Winckel H. 2003. In *IAU Symp. 209: Planetary Nebulae: Their Evolution and Role in the Universe*, ed. S Kwok, M Dopita, R Sutherland. San Francisco: Astron. Soc. Pac.
Van Winckel H, Cohen M, Gull TR. 2002. *Astron. Astrophys.* 390:147
Van Winckel H, Mathis JS, Waelkens C. 1992. *Nature* 356:500
Van Winckel H, Reyniers M. 2000. *Astron. Astrophys.* 354:135
Van Winckel H, Waelkens C, Fernie JD, Waters LBFM. 1999. *Astron. Astrophys.* 343:202
Van Winckel H, Waelkens C, Waters LBFM. 1995. *Astron. Astrophys.* 293:L25
Van Winckel H, Waelkens C, Waters LBFM. 2000. In *IAU Symposium 177: The Carbon Star Phenomenon*, ed. RF Wing, p. 285. Dordrecht: Kluwer
Van Winckel H, Waelkens C, Waters LBFM, Molster FJ, Udry S, Bakker EJ. 1998. *Astron. Astrophys.* 336:L17
Vassiliadis E, Wood PR. 1993. *Ap. J.* 413:641
Vassiliadis E, Wood PR. 1994. *Ap. J. Suppl.* 92:125
Venn KA. 1995. *Ap. J.* 449:839
Venn KA, Lambert DL. 1990. *Ap. J.* 363:234
Volk K, Kwok S, Hrivnak BJ. 1999. *Ap. J.* 516:L99
Volk KM, Kwok S. 1989. *Ap. J.* 342:345
von Helden G, Tielens AGGM, van Heijnsbergen D, Duncan MA, Hony S, et al. 2000. *Science* 288:313
Waelkens C, Van Winckel H, Bogaert E, Trams NR. 1991. *Astron. Astrophys.* 251:495
Waelkens C, Van Winckel H, Waters LBFM, Bakker EJ. 1996. *Astron. Astrophys.* 314:L17
Waelkens C, Waters LBFM, Cassatella A, Le Bertre T, Lamers HJGLM. 1987. *Astron. Astrophys.* 181:L5
Waelkens C, Waters LBFM, Van Winckel H, Daems K. 1995. *Astrophys. Space Sci.* 224:357
Wallerstein G. 2002. *Publ. Astron. Soc. Pac.* 114:689
Waters LBFM, Beintema DA, Zijlstra AA, de Koter A, Molster FJ, et al. 1998a. *Astron. Astrophys.* 331:L61
Waters LBFM, Cami J, de Jong T, Molster FJ, van Loon JT, et al. 1998b. *Nature* 391:868
Waters LBFM, Molster FJ, de Jong T, Beintema DA, Waelkens C, et al. 1996. *Astron. Astrophys.* 315:L361
Waters LBFM, Trams NR, Waelkens C. 1992. *Astron. Astrophys.* 262:L37
Waters LBFM, Waelkens C. 1998. *Annu. Rev. Astron. Astrophys.* 36:233
Waters LBFM, Waelkens C, Mayor M, Trams NR. 1993. *Astron. Astrophys.* 269:242
Weidemann V. 2000. *Astron. Astrophys.* 363:647
Weintraub DA, Kastner JH, Hines DC, Sahai R. 2000. *Ap. J.* 531:401

Werner K. 2001. *Astrophys. Space Sci.* 275:27

Whitelock P, Marang F. 2001. *MNRAS* 323:L13

Witt AN, Gordon KD, Furton DG. 1998. *Ap. J.* 501:L111

Yamamura I, Dominik C, de Jong T, Waters LBFM, Molster FJ. 2000. *Astron. Astrophys.* 363:629

Zijlstra AA, Chapman JM, te Lintel Hekkert P, Likkel L, Comeron F, et al. 2001. *MNRAS* 322:280

Zijlstra AA, Gaylard MJ, te Lintel Hekkert P, Menzies J, Nyman L-A, Schwarz HE. 1991. *Astron. Astrophys.* 243:L9

Zsoldos E. 1993. *Astron. Astrophys.* 268:149

Zuckerman B, Dyck HM. 1986. *Ap. J.* 311:345

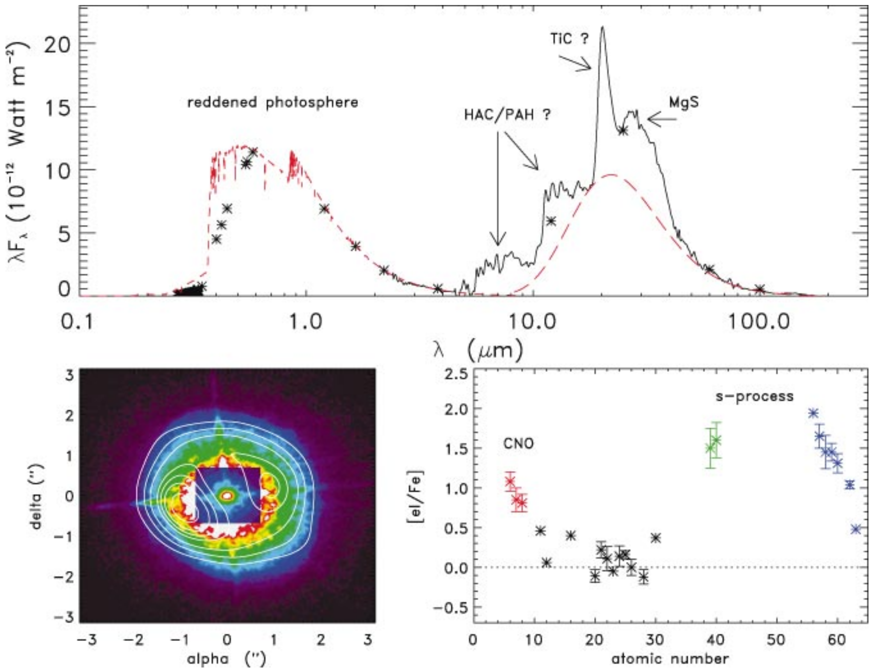

Figure 1 An illustration of the richness of the electromagnetic emission of post-AGB stars. The top panel is the observed spectral energy distribution of HD 56126, a C-rich, metal deficient ([Fe/H] = –1.0), post-AGB star: The double peaked energy distribution allows the study of direct light of the central star in the UV-optical domain while in the IR, the thermal emission from the circumstellar dust is well sampled by the ISO spectrum. The axes are such that surfaces scale to energy output. The reddened photospheric model and a modified black-body are shown in red. Note the nonstandard circumstellar extinction. The identification of several solid state bands and complexes are given (Hony et al. 2002). The lower left panel gives the *HST* snapshot image of the resolved nebula in scattered light by Ueta et al. (2000). The object is clearly resolved with a central bright star seen in direct light and a fainter halo in scattered light. Superimposed is the contour plot of the 11.8 μm image by Ueta et al. (2000), the latter indicating an equatorially enhanced superwind. The lower right panel gives the chemical composition of the C-rich central star, relative to the solar value. Note the very high overabundances of s-process elements (Van Winckel & Reyniers 2000), together with the high C-abundance. The light s-process species (Y, Zr) are given in green, the heavy ones (Ba, La, Ce, Pr, Nd, Sm, and Eu) in blue.