Late stages of Stellar Evolution *

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Abstract. A large fraction of ISO observing time was used to study the late stages of stellar evolution. Many molecular and solid state features, including crystalline silicates and the rotational lines of water vapour, were detected for the first time in the spectra of (post-)AGB stars. Their analysis has greatly improved our knowledge of stellar atmospheres and circumstellar environments. A surprising number of objects, particularly young planetary nebulae with Wolf-Rayet central stars, were found to exhibit emission features in their ISO spectra that are characteristic of both oxygen-rich and carbon-rich dust species, while far-IR observations of the PDR around NGC 7027 led to the first detections of the rotational line spectra of CH and CH^+.

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1. Introduction

ISO (Kessler et al., 1996, Kessler et al., 2003) has been tremendously important in the study of the final stages of stellar evolution. A substantial fraction of ISO observing time was used to observe different classes of evolved stars. IRAS had already shown the strong potential to discover many evolved stars with circumstellar shells in the infrared wavelength range. ISO provided the opportunity to extend this survey with higher sensitivity and spatial resolution, allowing many more sources to be detected in the inner regions of our Galaxy and in the Magellanic Clouds. But especially ISO's spectroscopic capabilities in the 2–200 μm wavelength range allowed a detailed study of individual objects through observations of gas-phase molecular bands, ionic forbidden lines and solid state bands. These studies are important not only to better understand the processes which dominate the final stages of stellar life but also because the interstellar medium is enriched in heavy elements from the mass lost by these stars during the last phases of their evolution.

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In the following sections, we will present highlights from the ISO observations of different classes of evolved stars: Asymptotic Giant Branch (AGB) stars, Post-AGB objects, Planetary Nebulae, Novae, Symbiotic stars and Wolf Rayet stars.

2. The Asymptotic Giant Branch stars

When low- and intermediate mass stars have exhausted hydrogen in their cores, they ascend the HR diagram to become cool giants, first on the Red Giant Branch (RGB) and later on the Asymptotic Giant Branch (AGB). These phases are characterized by substantial mass loss; in the AGB phase, the mass loss effectively drives stellar evolution. The low effective stellar temperatures as well as the copious amounts of circumstellar material that form as a consequence of this mass loss make these objects ideal targets in the infrared.

AGB stars have been extensively studied with the various instruments onboard ISO, and have greatly enhanced the understanding of the composition, dynamics and interaction of the stellar atmosphere and the surrounding circumstellar material. In particular, SWS (de Graauw et al., 1996, Leech et al., 2003) and LWS (Clegg et al., 1996, Gry et al., 2003) have greatly enhanced our knowledge of the composition of the molecular envelope and the sometimes thick dust shells surrounding these stars, while the sensitivity of ISOCAM (Cesarsky et al., 1996, Blommaert et al., 2003) greatly extended our knowledge of the fundamental properties of tens of thousands giant stars.

2.1. Molecules in the Stellar atmospheres...

AGB stars are generally divided into oxygen-rich and carbon-rich stars. All stars start of with a photospheric C/O ratio which is lower than unity; during the evolution on the AGB however, dredge-ups bring freshly processed carbon to the surface, and gradually enriche the atmosphere in carbon. Depending (mainly) on initial mass, some stars eventually experience a carbon preponderance in their atmosphere, and then they are called carbon stars.

AGB stars have very extended and relatively cool (typically 3000 K) atmospheres, allowing the formation of molecules in the stellar atmospheres. As the stellar envelope material cools down, CO is about the first molecule to be formed. This process is so efficient (and CO so stable) that for O-rich stars virtually all carbon is locked up in CO, leaving only oxygen for further chemistry. For carbon stars, all oxygen is locked up in CO and the chemistry is carbon-driven. The difference in spectral appearance is enormous, both in the molecular and dust contents (see Tables I and II).

The presence of molecules can easily be inferred through their ro-vibrational bands in the infrared. Such molecular bands have been used – amongst others

– with great success to extend the MK classification to the infrared (Vandenbussche et al., 2002) and to improve the calibration of SWS (see Decin et al., 2003) using detailed models for A0 – M2 stars; in turn, the SWS observations yielded many improvements in the models. Different molecules turn out to be sensitive to different stellar parameters, thereby allowing to determine these stellar parameters from the ISO observations. The ISO observations of molecular bands have revealed the importance of fundamentally new ideas about modeling of such stars; one example is the development of fully consistent hydrodynamical codes which include a frequency-dependent radiative transfer (see e.g. Höfner, 1999; Gautschy-Loidl et al., 2004).

2.2. ...AND BEYOND : THE ”EXTENDED” ATMOSPHERE OF AGB STARS

However, early in the ISO lifetime, it became clear that the molecular absorption seen in the SWS spectra of several O-rich AGB stars is quite different than was expected from detailed hydrostatic model calculations. Tsuji et al. (1997) noticed that CO and SiO absorption in early M giants was weaker than expected, while water vapour and CO_2 bands much stronger than predicted; in fact, the latter molecule was not predicted to be present in the stellar atmosphere at all. They found that the molecular features due to CO, CO_2 and SiO correspond to excitation temperatures in the range 750 – 1250 K, indicating that they originate outside the stellar photosphere. This led to the terminology “extended atmosphere”, “warm molecular layer” or simply MOLsphere to denote that region close to the stellar photosphere (typically up to a few $R_\star$) where this excess molecular absorption or emission originates from and corresponds to a quasi-static molecular zone that was already hypothesized to exist based on ground-based data.

Soon, a wealth of molecular bands from this extended atmosphere were discovered and/or analyzed (see Table I). These molecular bands are now used as probes to map the physical conditions (such as temperature and density) in the direct surroundings of the AGB stars (e.g. Cami et al., 2000; Justtanont et al., 2004).

Of particular importance is water vapour. Water vapour is detected in both SWS and LWS spectra of O-rich AGB stars (and many others – see Cernicharo and Crovisier, this volume) through literally millions of spectral lines, and is the source for large differences in spectral appearance between Semi-Regulars and Miras. For Semi-Regulars, water vapour is just a component in the spectra up to 10 μm, and the overall continuum shape is still determined by the stellar photosphere. In Mira variables on the other hand, the water vapour layer is dense, and due to the large opacity over a large wavelength range, this layer determines the shape of the IR continuum up to at least 10 μm in these objects. Analyses based on SWS observations suggested that this semiopaque layer typically extends to $\sim$ 2 $R_\star$; this turns out to be in good agreement

Table I. Overview of molecular bands and dust features reported in ISO observations of O-rich AGB stars. For an overview of the silicate dust we refer to Molster and Kemper, this volume.

Component		λ (μm)	References
		Molecular features	
H_2O		2.3 – 197	[1–20,29]
OH		2.80 – 4.00	[2,4,13–18]
CO	Fundamental	4.6	[2,4,14–19]
	First overtone	2.3	[2,4,14–19]
SiO	Fundamental	8.0	[5,14–19]
	First overtone	4.0	[2,4,13–19]
CO_2	ν_3 asymmetric stretch	4.2	[2,4,6,14,15,17,18]
	ν_2 bending	14.96	[3,6,9,14,15,17,18,24,28]
	various combination bands	12 – 18	[3,6,9,14,15,17,18,24]
SO_2	ν_3 asymmetric stretch	7.55	[5,15,17,18]
		Dust features	
Magnesiowüstite	$Mg_{(1-x)}Fe_xO$	19.5	[15,21,24]
Alumina	Al_2O_3	11.0	[15,21]
Spinel	$MgAl_2O_4$	13.0	[15,22,23,24]
Crystalline water ice		43,60	[25,26]
Metallic Fe		2–10	[27]

[1]Neufeld et al., 1996; [2]Tsuji et al., 1997; [3]Justtanont et al., 1998; [4]Yamamura et al., 1999a; [5]Yamamura et al., 1999b; [6]Cami et al., 2000; [7]Tsuji, 2000; [8]Zubko and Elitzur, 2000; [9]Markwick and Millar, 2000; [10]Tsuji, 2001; [11]Jørgensen et al., 2001; [12]Jones et al., 2002; [13]Matsuura et al., 2002a; [14]Matsuura et al., 2002b; [15]Cami, 2002; [16]Decin et al., 2003; [17]Van Malderen, 2003; [18]Justtanont et al., 2004; [19]Van Malderen et al., 2004; [20]Truong-Bach et al., 1999; [21]Posch et al., 2002; [22]Posch et al., 1999; [23]Fabian et al., 2001; [24]Sloan et al., 2003; [25]Sylvester et al., 1999; [26]Dijkstra et al., 2003a; [27]Kemper et al., 2002a; [28]Ryde et al., 1999; [29]Barlow et al., 1996

with interferometric observations in the infrared (Cami, 2003). Also, the pure rotational H_2O lines were first detected in the SWS (Neufeld et al., 1996) and LWS (Barlow et al., 1996) spectra of AGB stars.

Molecular bands are also detected in the spectra of carbon stars. Absorption features due to C_2, HCN (and HNC), C_2H_2 and C_3 are commonly detected (see Table II); moreover, some (likely molecular) features detected in the SWS spectra are still unidentified (Yang et al., 2004). While the excitation temperatures of these molecular bands are in some cases comparable to the

Table II. Overview of molecular bands and dust features reported in ISO observations of C-rich AGB stars

Component		λ (μm)	References
	Molecular features		
CO	Fundamental	4.6	[1,2,4,8]
CH	Fundamental	3.3 – 4.1	[4,8]
CS	1st overtone	3.9 – 4.2	[1,4,8]
	Fundamental	7–8	[1,4,5,8]
SiS	1st overtone	6.6–7	[4]
HCN	Various bands	2.58–3.86	[1,2,4,7,8]
	$2\nu_2$	7.0	[1,4,8]
	ν_2	14.04	[1,5,6,8]
	$2\nu_2^0 - \nu_2^1$	14.30	[5,6,8]
C_3		5.2	[1,2,3,8]
C_2H_2	ν_3	3.05	[1,2,8]
	Various bands	3.8	[1,2,8]
	$\nu_4 + \nu_5$	7–8	[1,2,5,8]
	ν_5	13.7	[1,2,6,8]
	Dust features		
SiC		11.3	[2]
MgS		26–35	[2,9]

[1]Jørgensen et al., 2000; [2]Yang et al., 2004; [3]Hron et al., 1999; [4]Aoki et al., 1998; [5]Aoki et al., 1999; [6]Yamamura et al., 1999c; [7]Harris et al., 2003; [8]Gautschy-Loidl et al., 2004; [9]Hony et al., 2002a

molecular bands in the O-rich stars, there is still debate about the exact origin of these molecular bands (see e.g. Jørgensen et al., 2000). It is clear however that also for the carbon stars, the ISO observations have greatly expanded the possibilities to study the stellar and (possibly) circumstellar envelope.

2.3. DUST

The importance of ISO observations for the study of circumstellar dust can hardly be overestimated. The discovery of crystalline silicates in a wide variety of objects (see Molster and Kemper, this volume) and its consequences for the study of circumstellar and interstellar dust opened up the field of astromineralogy. Observations with SWS and LWS have resulted in the detection and identification of many more dust components in the circumstellar dust shells of AGB stars, and shed new light of the pathways to dust formation. Moreover, ISO observations have allowed to directly link the molecular to the dust content in these stars (see e.g. Cami, 2002; Sloan et al., 2003).

In the spectra of O-rich stars with low mass loss rates, the typical silicate bands commonly found in Miras are often at most a minor component in the dust spectra. In these stars, prominent features in the ISO data have provided convincing evidence for a prominent role played by simple oxides such as Al_2O_3 (11 μm) or MgFeO (19.5 μm). The famous 13 μm feature (already detected in IRAS-LRS spectra, see Vardya et al., 1986) is attributed to spinel ($MgAl_2O_4$, Posch et al., 1999, Fabian et al., 2001) although there is still a lively debate about this identification. For instance, Sloan et al. (2003) find no correlation between the 13 μm feature and an observed band at 32 μm which was also presumably due to spinel.

For stars with higher mass loss rates, silicates (both amorphous and crystalline) are the dominant dust component (see Molster and Kemper, this volume). Also the presence of crystalline water ice and metallic Fe has been demonstrated in these stars. Many more components (especially at longer wavelengths) can be observed in more evolved stars (post-AGB and PNe, see later sections).

For the carbon stars, the situation is quite different. The bulk of the dust is in the form of amorphous carbon, which determines the energy distribution but has no resonances in the IR. Most energy distributions of the carbon stars seem to follow a sequence of decreasing T_{NIR} which is interpreted as a cooling and thickening of the circumstellar dust shell. The infrared spectra of carbon stars furthermore show only a small number of solid state bands. Commonly detected dust features include the 11.3 μm feature due to SiC (Gilra, 1973) and the ”30 μm feature” which is believed to be due to MgS (see e.g. Hony et al., 2002a).

A particular class of objects are the “mixed chemistry” objects. Those are stars which show the presence of typically O-rich and C-rich dust at the same time. In all known cases, the O-rich material is cool and often highly crystalline, while the star itself and/or a warm dust component are typically C-rich. While such objects might represent stars that have only recently become a carbon star, it turns out that most of the well studied objects in this class belong to a binary system. In such cases, the O-rich material is stored in a disk around the companion star (see e.g. Yamamura et al., 2000) or in a circumbinary disk (such as in the Red Rectangle, see Waters et al., 1998a).

2.4. Studies of AGB stars in different environments

Mid-infrared studies before ISO were mostly limited to relatively nearby objects; this was especially true for spectroscopical studies. ISO provided the sensitivity and the spatial resolution to investigate AGB stars in the inner regions of the Milky Way galaxy and in the Magellanic Clouds. Studies in these regions offer several advantages, first it allows to study different populations (different metallicities) and second, often the distance is known and thus the luminosities.

2.4.1. *The inner Milky Way*

The second largest program performed with the ISO satellite, called ISOGAL, is a mid-infrared survey along the galactic plane, performed with ISOCAM (Omont et al., 2003). About 16 square degrees were observed mostly at 2 wavelengths: 7 and 15 μm. In comparison with IRAS, this survey provides data that are 2 orders of magnitude more sensitive and have one order of magnitude higher spatial resolution. A systematic cross-identification with near-infrared (I, J, K_s) DENIS (Epchtein et al., 1997) sources was performed for the ISOGAL detected sources. This has led to a five-wavelengths ISOGAL catalogue which can be obtained through *VizieR*.

Several papers describe results on AGB stars obtained on fields towards the galactic Bulge where the extinction is less strong than along the plane. Figure 1 shows a [15] vs $(K_s\text{-}[15])_o$ diagram of bulge ISOGAL sources, taken from Ojha et al. (2003). A clear linear sequence of increasing $(K_s\text{-}[15])_o$ colour for brighter 15μm fluxes can be seen, as was also originally presented in the earlier Omont et al. (1999) paper for the [15] vs [7]-[15] diagram. The increasing red colour of $(K_s\text{-}[15])_o$ as function of [15], can be explained by an increasing mass-loss rate. The exact amount of the mass loss rate is model-dependent, but is in the order of 10^{-9} to a few 10^{-7} $M_\odot$/yr (Ojha et al., 2003) for the sources in the sequence and higher for the redder sources ($(K_s\text{-}[15])_o > 2.5$) which are identified as Mira variables (see below). An important point to mention is that the relatively low mass-loss rates observed by the 15 μm excess cannot be observed through the near-infrared colours.

Omont et al. (1999) and Glass et al. (1999) demonstrated that the observed sources are red giants above the RGB limit. A comparison by Glass et al. (1999) and Glass & Schultheis (2002) of ISOGAL data with a spectroscopic survey of Baade's window NGC 6522, shows that M giants as early as M2 are detected by ISOGAL but that it is complete from M5 onwards.

A further investigation of the circumstellar dust of the mass losing AGB stars comes from ISOCAM Circular Variable Filters measurements. About 20 sources were oberved in three bulge fields (5-17 μm). As was expected from the colours, several show clear evidence of a mid-IR excess related to the circumstellar dust (Blommaert et al., 2000 and in preparation). Most sources

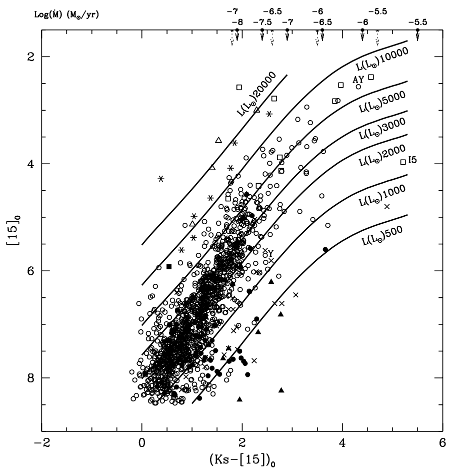

Figure 1. ISOGAL [15] versus $(K_S\text{-}[15])_o$ diagram of galactic bulge sources, taken from Ojha et al (2003). The different symbols are used to indicate sources for which different sorts of associations or data exist. The curves represent sequences of luminosities ranging from 500 to 20,000 $L_\odot$, with increasing mass-loss rates. The approximate scales of mass-loss rates are displayed at the top. For further details on how these were derived see Ojha et al. (2003)

do not show the typical relatively peaked silicate 9.7 μm feature, but rather a broad feature with a maximum peaking at longer ($\sim$ 12μm) wavelengths. Such features are known from previous work on IRAS data (Sloan & Price, 1995 and references therein). They have been associated with amorphous alu-

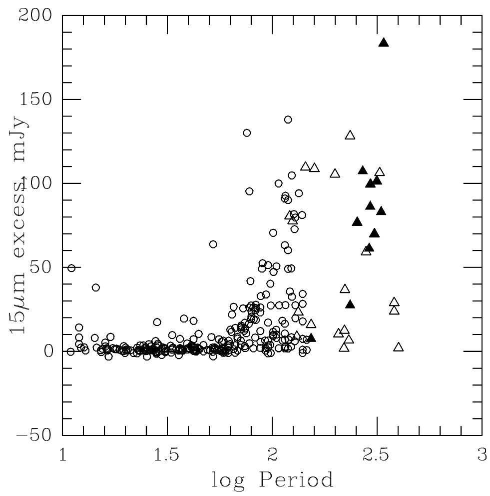

Figure 2. 15 μm excess (indicative of mass loss) versus log(Period (days)), taken from Alard et al. (2001).

minium oxide grains (Onaka et al., 1989, Speck et al., 2000a). Such features are mostly seen in low mass-loss rate sources, confirming the interpretation that ISOGAL is mainly detecting the onset of mass-loss on the AGB.

Another important characteristic of AGB stars is their variability. Typical examples are Mira and Semi-Regular variables, with periods in the range of hundred to a few hundred days. Mass loss and variability are related in the sense that the longer period, and larger amplitude variable stars also show higher mass loss rates with the extreme examples being the OH/IR stars which have the longest periods (up to a thousand days) and the highest mass loss rates ($\sim 10^{-5}$ $M_{\odot}$/yr). Alard et al. (2001) and later also Glass & Schultheis (2002) combined the ISOGAL data with data coming from the gravitational lensing experiment MACHO for the Baade windows. In comparison to earlier searches for variable stars (e.g. Lloyd Evans 1976), the new surveys find variability down to much smaller amplitudes (0.5 mag compared to better than 0.1 mag). Alard et al. (2001) conclude that almost all sources detected at 7 and 15 μm and thus above the RGB-limit are variable. A period of 70 days or longer is a necessary but not a sufficient condition for mass loss to occur (Figure 2).

ISOGAL also allows to study the AGB stars as tracers for the underlying stellar population. First results are given in van Loon et al. (2003) for the Bulge.

The ISOGAL survey was also used to find the most extreme mass-loss rate AGB stars near the Galactic Centre. Ortiz et al. (2002) found infrared counterparts for all the objects detected in the OH (1612 MHz) maser surveys of the Galactic Centre. Blommaert (2003) observed the Spectral Energy Distributions of a sample of 26 OH/IR stars in the wavelength range of 2-60 μm. The main results from these studies are that the peak of the bolometric magnitude distribution falls at -5 and that only a relatively small number of stars has high luminosities (and thus less than 1 Gyr old). The OH/IR stars fall predominantly below the extension of the Mira Period-Luminosity relation. Through the modelling of the SEDs, individual total mass loss rates were determined, which range from 10^{-6} to $10^{-4} M_{\odot}/\mathrm{yr}$.

2.4.2. *The Magellanic Clouds*

Studying the AGB stars in the Magellanic Clouds has the advantage that the distances and thus the luminosities are known. ISO photometry and spectroscopy of a sample of 57 bright AGB stars and Red SuperGiants in the LMC are presented in Trams et al. (1999b). The sources were selected on basis of IRAS colours indicative of high mass-loss rates. From ISO colour-colour diagrams and the spectra, the spectral type of the dust was determined. About half the sample are classified as carbon stars. No M stars with carbon-rich dust were found, suggesting that Hot Bottom Burning (HBB) cannot efficiently turn back carbon stars into oxygen-rich ones. Mass-loss rates and luminosities for this sample have been determined by van Loon et al. (1999), using a radiative transfer code. The dust-enshrouded carbon stars are generally brighter than the optically bright carbon stars but less bright than the high mass-loss M-type ones. The interpretation given is that only stars between 2 and 4 $M_\odot$ become carbon stars whereas more massive stars remain oxygen-rich because of HBB. The existence of a few luminous carbon stars may be explained by HBB switching off near the very tip of the AGB and the occurrence of a final thermal pulse thereafter. Connected to this is the first detection of silicate dust around a carbon star (Trams et al. 1999a). In contrast to galactic carbon stars with silicate dust, IRAS04496-6958 is very luminous ($M_{bol} = -6.8$). Possibly, the silicate dust is a trace of its oxygen-rich past and it became carbon-rich after its last thermal pulse. Most of the supergiants have lower mass-loss rates than the mass consumption rate by nuclear burning. Only 2 have a much higher mass-loss rate, suggesting that the RSGs lose most of their mantles in very short phases. Also AGB stars have episodes of intensified mass loss rates, but the mass loss rate is always higher than the nuclear burning rate.

Blommaert et al. (1999) studied the IRAS sources towards the SMC and find similar results as for the LMC study. There are however, no Carbon stars with luminosities near the AGB limit. All stars suffer extreme high mass loss rates ($\dot{M} > 10^{-5}$ $M_\odot/yr$), even stars with relatively low masses (~ 1 $M_\odot$).

The above studies are based on sources which were already known from the IRAS survey and are thus restricted to the brightest AGB stars. ISOCAM was also used to detect new and lower luminosity AGB stars. Tanabé et al. 1998 performed a survey of MC clusters and detected very red stars at $M_{bol} = -4.5$. High mass loss rates can thus also be obtained by lower luminosity stars with likely lower initial masses. Another survey with ISOCAM was performed at 4.5, 6.7 and 12 μm on several regions of the Large and Small Magellanic Clouds (Loup et al., 1999). First results were discussed in Cioni et al. (2003), who combined the ISO data with 2MASS and DENIS near-infrared data and light-curves extracted from the MACHO database. They confirmed the AGB or supergiant nature of the detected point sources and classified the AGB stars in Mira or Semi-Regular pulsators.

3. Post–AGB stars

The AGB phase of stellar evolution ends in an episode of extremely high mass loss (so-called superwind), in which the mass loss rate exceeds $10^{-5} M_\odot yr^{-1}$. The high mass loss during the end of AGB evolution creates a circumstellar envelope which may completely obscure the star. The superwind rapidly strips the star of virtually its entire envelope, thus effectively terminating the AGB phase. The central star subsequently evolves to higher temperatures on a timescale that depends on its mass and, at the same time, the ejected envelope expands and cools. The star is now in the post-AGB phase and depending on the rate of its evolution, the star may start to photoionize the ejected material, forming a Planetary Nebula (PN). Post-AGB objects hold the key to understanding how largely spherical AGB circumstellar shells transform into diverse aspherical morphologies (see e.g. Ueta et al., 2000 and references therein).

The post-AGB objects which will become Planetary Nebulae *in the near future* are called proto-planetary nebulae (PPNe). Since masses of the central stars and therefore timescales of their evolution are very uncertain, the term proto-planetary nebula usually expresses only our belief that a PN will be created. In this review, however, both terms: *post-AGB object* and *proto-PN* will be used equivalently unless there are strong arguments suggesting that a PN will not be formed. For more detailed discussion of the post-AGB phase of stellar evolution the reader is referred to the Toruń Conference Proceedings: *Post-AGB objects as a phase of stellar evolution* (edited by Szczerba and Górny, 2001) and to the recent reviews by van Winckel (2003) and by Waelkens and Waters (2004)

Just like in the previous sections, ISO results related to post-AGB objects with O-rich and C-rich circumstellar shells are discussed separately. A special importance will be given to the signatures of mixed chemistry.

3.1. POST-AGB OBJECTS WITH O-RICH CIRCUMSTELLAR SHELLS

As far as dust is concerned, the most important ISO discovery seems to be detection of crystalline silicates from both young and old stars. Lack of crystalline silicate features in the interstellar medium probably means that after their formation during stars' death they do not survive until new stars are born. In a series of papers (Molster et al., 2002a; Molster et al., 2002b; Molster et al., 2002c) crystalline silicate features are investigated in the ISO spectra of 17 O-rich circumstellar dust shells surrounding evolved stars. The considered sample contains 6 post-AGB objects and HD 179821, for which it is yet a matter of debate whether this object is a massive supergiant or a low-mass object in its post-AGB phase of evolution. Apart from the broad 10 and 18 μm bands that are due to amorphous silicates, Molster et al. found at least 49 narrow bands between 10 and 60 μm (divided into 7 complexes), which can be attributed to crystalline silicates (olivines and pyroxenes). The richness of the crystalline silicate features in the ISO spectra contains important information related to the conditions in which the grains were formed and processed. It allows detailed studies of the mineralogy of these dust shells. Note, however, that abundances of crystalline silicates are rather low and do not exceed about 10-15 % of the total amount of silicates (see Molster, 2000 and references therein).

Molster et al. found that the crystalline silicate band strengths correlate with the geometry of circumstellar environment: disk (strong) or outflow sources (weak crystalline silicate bands). It has been suggested that in disk sources low temperature crystallization may take place (Molster et al., 1999), while in outflow sources high temperature crystallization in layers which are close to the star is more probable. Among 6 analyzed post-AGB stars, 4 possibly have disk and two are classified as outflow sources. It is worth to note that two of the disk sources (Red Rectangle and Roberts 22) show also carbon-rich dust as evidenced by the Policyclic Aromatic Hydrocarbon (PAH) features. The PAHs are predominantly present in the scattering lobes, while the crystalline silicates are expected to be present in the disks (Waters et al., 1998a).

A full 2-200 μm ISO spectrum was used to constrain the dust properties in a post-AGB star HD 161796 (Hoogzaad et al., 2002). A good fit to the spectral energy distribution was achieved using four co-spatial but distinct dust components: amorphous silicates (63 %), forsterite (4 %), enstatite (6 %) and crystalline water ice (27 %). The derived temperature of water ice suggest that the ice must be formed as a mantle on top of an amorphous silicate core, which requires high mass loss rates, exceeding $5 \times 10^{-5} M_{\odot} yr^{-1}$. The derived mass loss rate is high enough to allow for this process to be efficient.

An interesting example of OH/IR post-AGB star, still obscured by the ejected material, is IRAS 16342−3814 (OH 344.1+5.8, also called "the water fountain nebula"). This source is classified as a proto-PN (Sahai et al., 1999) and is the only OH/IR star known to have crystalline silicate absorption features seen up to almost 45 μm in its SWS spectrum (Dijkstra et al., 2003b). This suggests that IRAS 16342− 3814 recently had an extremely high mass loss rate and is perhaps the youngest PPN observed until now. Besides the crystalline silicates (forsterite, diopside and possibly clino-enstatite) identified in the SWS spectrum, also crystalline water ice is detected. In the LWS spectrum an unidentified feature at 48 μm is seen.

A deep and wide water ice band at 3.05 μm is seen also in another young OH/IR PPN: IRAS 22036+5306 (Sahai et al., 2003), together with wide absorption by silicates around 10 μm and a 60 μm feature, perhaps due to crystalline H_2O-ice (the absence of a corresponding 43 μm H_2O-ice feature may be due to a decline in its strength at low temperatures - Dijkstra et al., 2003a). The freeze-out of water onto dust grains indicated by the ice features requires high densities, which are likely to be characteristic of the dusty disk seen in the Hubble Space Telescope image. In addition, in the SWS spectrum of this object an unidentified feature at 3.83 μm (tentatively attributed to the H_2S) is detected.

A sample composed of O-rich PPNe has been observed with the ISO spectrometers to search for atomic fine-structure lines (Castro-Carrizo et al., 2001). The low-excitation transitions of [O I], [C II], [N II], [Si I], [S I], [Fe I] and [Fe II] were observed. Taking into account the sample of C-rich PPNe presented by Fong et al. (2001) (see Section 3.2), they concluded that PPNe emit in these atomic transitions only when the central star is hotter than about 10 000 K. This result suggests that such lines predominantly arise from photodissociation regions, and not from the shocked regions.

3.2. POST-AGB OBJECTS WITH C-RICH CIRCUMSTELLAR SHELLS

ISO-SWS observations of C-rich proto-planetary nebulae have been discussed by Hrivnak et al. (2000) with emphasis given to wavelengths longer than about 20 μm. At these wavelengths prominent dust features at 21 μm and around 30 μm are seen. The 21 μm band has been discovered by Kwok et al. (1989) in the IRAS Low Resolution spectra of some C-rich PPNe, while the 30 μm band in this class of objects has been detected in the Kuiper Airborne Observatory spectra by Omont et al. (1995). The 21 μm feature is not seen in the spectra of either the precursors to PPNe or the successors of PPNe. Note, however, that Hony et al. (2001b) reported tentative detection of this feature in two planetary nebulae with [WR] central stars, while Pei and Volk (2003) reported its detection in planetary nebula IC 418, and Volk et al. (2000) suggested possible presence of this band in two extreme carbon stars. On the other hand, the 30 μm band has been detected first in some C-rich AGB stars and in C-rich Planetary Nebulae (see Omont et al., 1995 and references therein).

Thanks to the ISO observations, Volk et al. (1999) were able to obtain an intrinsic profile of the 21 μm feature, in fact centered at 20.1 μm. This feature has been attributed to various molecular and solid-state species, none of which satisfy all constraints, although titanium carbide, PAHs and even silicon carbide (see discussion in Speck and Hofmeister, 2004 and references therein) seem to be the most favored candidates. On the other hand, in spite of some problems with the SWS data above 26 μm it seems that the 30 μm feature is not so smooth as the 21 μm one and, instead, shows a kind of substructure (Szczerba et al., 1999). In fact, analysis of the ISO data for other post-AGB sources apparently resolves the 30 μm feature into two components at about 26 and 33 μm (Volk et al., 2002). The derived intrinsic profiles for these features opens a possibility to search for their carrier(s). Recently, Hony et al. (2002a) analyzed ISO spectra of C-rich sources including low mass carbon stars, extreme carbon stars, post-AGB objects and planetary nebulae. They modeled the whole range of the extracted “30” μm band profiles by using magnesium sulfide. They argued that in some sources a residual emission at approximately 26 μm can also be fitted using MgS grains but with a different grains shape distribution. The further strengthening of the MgS identification as a carrier of the “30” μm feature comes from detailed modeling of HD 56126, one of the post-AGB "21 μm object" (see Hony et al., 2003).

The ISO spectra of C-rich sources show many dust features including Unidentified Infrared Bands (UIRs), which are attributed very often to PAHs (see a comprehensive review by Tielens et al., 1999 and Hony et al., 2001a). Besides the well known UIR bands at 3.3, 6.2, 7.7, 8.6 and 11.3 μm, ISO has revealed a wealth variety of weaker features, satellite bands and sub-features. While the final identification of the carrier(s) responsible for these features is still under discussion, there is an agreement that the observed UIR bands are very characteristic for aromatic structures (the C-atoms are arranged in planar hexagons – like in graphite – with attached hydrogen atoms at the edges). A detailed analysis of SWS spectra for different kind of objects (Peeters et al., 2002), demonstrated that the UIR emission features in the region 6-9 μm clearly show profile variations. The observed variations in the characteristics of the UIR emission bands are linked to the local physical conditions, but they do not reflect - at least at first glance - a clear link between PAH spectrum and the post-AGB source evolutionary state (see Peeters et al., 2002 and Peeters et al., this volume, for details). ISO observations of post-AGB objects demonstrated that there is an evolution of carbonaceous material from aliphatic structures (the C–atoms are arranged on a tetrahedral network - like in diamond – with attached H atoms at the edges) to the aromatic structures during the evolution from the proto-planetary to the planetary nebulae phase (Kwok et al., 1999, Kwok et al., 2001).

AFGL 618 and AFGL 2688 were the first stars (already 30 years ago) to be considered to be in transition from AGB to PN, and they are now the best investigated sources among PPNe. When ISO results are discussed for C-rich proto-planetary nebulae, very often these two objects are given as an example and in this review the situation will be similar. Let us start with polarimetric imaging of AFGL 2688 at 4.5 μm with ISOCAM which allowed to conclude that the polarization of starlight induced by dust grains is almost independent of wavelength between 2 and 4.5 μm (Kastner et al., 2000). This finding indicates that scattering dominates over thermal emission at these wavelengths, and that the dust grains have characteristic radii less than 1 μm.

ISOPHOT (Lemke et al., 1996, Laureijs et al., 2003) linear scans of AFGL 2688 and AFGL 618 demonstrated that both these objects have extremely extended dust shells (see Speck et al., 2000b). Assuming constant expansion velocities, ages for these dust shells are of the order of 10^5 years. The infrared intensities show "periodic" enhancements, timescales for which (few times 10^4 years) coincide with thermal pulses on the AGB.

ISO spectroscopy allowed also to detect molecular bands in spectra of some C-rich post-AGB objects. For example, Cernicharo et al. (2002) reported the detection of a molecular band at 57.5 μm in proto-planetary nebulae AFGL 618 and AFGL 2688 that has been tentatively assigned to the ν_5

bending mode of C_4. Polyynes such as C_2H_2, C_4H_2 and C_6H_2, and single aromatic species such as benzene, have been detected in AFGL 618 (Cernicharo et al., 2001a, Cernicharo et al., 2001b). These discoveries support the idea that more complex C-rich molecules could be formed in space. However, the mechanisms allowing the growth of carbon-rich molecules are still poorly known, and the full set of molecules that could participate in the chemical reactions leading to the formation of large complex carbon-rich species has yet to be identified.

Analysis of the LWS spectra for the two above mentioned PPNe allowed to detect rotational lines of ^{12}CO (J=14-13 to J=41-40) and lines of ^{13}CO (J=14-13 to J=19-18), as well as HCN and HNC (Justtanont et al., 2000, Herpin et al., 2002). In the early stages, represented by AFGL 2688, the longwave emission is dominated by CO lines. In the more advanced stage (AFGL 618), very fast outflows are present, which, together with the strong UV radiation field from the central star, dissociate CO. The released atomic oxygen allows formation of new O-bearing species, such as H_2O and OH, in a C-rich environment. In case of AFGL 618, several lines of OH and H_2O are detected (Herpin and Cernicharo, 2000, Herpin et al., 2002). In CRL 618 the abundance of HNC is enhanced with respect to HCN as a result of chemical processes occurring in the photodisociation region.

HR 4049 was first suggested to be an object in the transition phase from the AGB to PN stage by Lamers et al. (1986) who discovered both a large IR excess and severe UV deficiency indicating the presence of circumstellar dust. Presently, the source is considered to be the prototype of a group of post-AGB stars in a binary system with extremely metal-depleted atmospheres (van Winckel et al., 1995). The ISO/SWS spectrum of this object shows the signatures of C-rich dust (PAHs - Beintema et al., 1996) and the presence of O-rich gas (isotopomers of CO_2 - Cami and Yamamura, 2001). Analysis of the ISO/SWS spectrum together with other literature data allowed to propose that a very optically thick circumbinary disk could be response for the observed IR emission from HR 4049 (Dominik et al., 2003).

A sample composed of C-rich PPNe has been observed with the ISO spectrometers to search for atomic fine-structure lines (Fong et al., 2001). The low-excitation transitions of [O I], [C II], [Si I], [Si II], [S I], [Fe I], [Fe II], [Ne II] and [N II] were observed. However, only few lines in few proto-planetary nebulae were detected.

3.3. Other post-AGB objects

There are two classes of objects that, on the basis of their photospheric abundances, pulsation properties and circumstellar material have been classified as post-AGB stars. They are RV Tau stars and R CrB stars. Both groups of objects are known to have circumstellar dust, giving support to their evolved nature. There are few RV Tau stars observed with ISO. The typical SWS spectrum shows emission bands of amorphous silicates at 10 and 18 μm (see e.g. Szczerba et al., 2003). However, as demonstrated by van Winckel et al. (1998) in case of AC Her, the unusual broad feature at 8–12 μm is due to a high crystallization fraction of the circumstellar silicates. The authors argued that the circumstellar material is trapped in a long-lived disk in the system similar to what is observed in the case of the Red Rectangle. Matsuura et al. (2002b) analyzed SWS spectra of the RV Tau star, R Scuti and demonstrated that that spectra are dominated by H_2O emission bands with CO, SiO and CO_2 bands also present. They argued, however, that R Sct may be a thermally pulsing AGB star, observed in a helium burning phase. Lambert et al. (2001) discussed spectra of some R Coronae Borealis stars. They reported detection of the sharp emission features, which coincides with those of UIRs, only in one of the analyzed objects, V 854 Cen. The features coincide with those from laboratory samples of hydrogenated amorphous carbon. Since V 854 Cen, is of order of 1000 more abundant in hydrogen than other typical R CrB stars, the emission features are probably from a carrier containing hydrogen. The extreme H-deficiency of the R CrB stars suggests that during their evolution some mechanism removed the entire H-rich stellar envelope. This may be related to a thermal pulse after the star left the AGB. A similar scenario probably applies to “Sakurai’s object”, a star that has experienced dramatic changes during the last decade. The ISO data demonstrate the presence of hot circumstellar dust around this star (Eyres et al., 1998a, Kerber et al., 1999).

There is a group of less massive post-AGB objects with central stars of B spectral type (so-called hot post-AGB stars) which have small or even do not have at all infrared excess. One should be aware, however, that a group of Herbig Ae/Be stars (young intermediate-mass pre-main-sequence stars) can be easily confused with such post-AGB candidates. The ISO observations allowed to detect C- and O-rich dust features in SWS spectra of some hot post-AGB candidates (Gauba and Parthasarathy, 2004), thus indicating the dominant chemistry (C- or O-based) in the circumstellar dust shells and their central stars.

Let us finish this part on post-AGB stars with an attempt to classify SWS01 spectra for 61 proto-planetary nebuale by Szczerba et al. (2003). The main dust and/or molecular features were taken into account to propose a division of all spectra into 7 classes (4 for C-rich and 3 for O-rich sources). On the basis of their classification they discussed the connection between post-AGB objects and planetary nebulae with emphasis on possible precursors of PNe with [WR] central stars.

4. Planetary Nebulae and Pre-Planetary Nebulae

We have seen earlier in this chapter that the terms 'protoplanetary nebulae' and 'post-AGB objects' are often used interchangeably to denote objects that have left the AGB but have not yet developed significant photo-ionized regions. We include 'pre-planetary nebulae' in this group too; the term is sometimes taken to mean that signs of the early development of a circumstellar photoionized region are present for objects in this category.

4.1. PN AND PRE-PN WITH DUAL DUST CHEMISTRIES

ISO targeted many O-rich and C-rich objects for spectroscopy using the SWS and LWS instruments; the enormous wavelength coverage (2.4–197 μm) that these two instruments delivered, together with their improved sensitivity relative to NASA's pioneering *Kuiper Airborne Observatory*, led to the discovery of many new dust spectral features. One of the big surprises was the relatively high incidence of objects that simultaneously exhibit dust features from both O-rich and C-rich carriers. Ever since its discovery, the Red Rectangle, AFGL 915, has been considered to exhibit the archetypal 3–13 μm UIR-band spectrum (usually attributed to aromatic carbon species, such as PAHs), yet the SWS spectrum of this object shows many crystalline silicate emission features longwards of 20 μm (Waters et al. 1998a). Waters et al. (1998b) found that two planetary nebulae with strong UIR-band spectra, BD+30^{o}3639 and He 2-113, also exhibited a similar array of crystalline silicate emission features longwards of 20 μm. These two nebulae both have carbon-rich nebulae and cool late-type [WCL] Wolf-Rayet central stars, as does CPD–56^{o}8032, which Barlow (1997) and Cohen et al. (1999) found to exhibit emission features due to crystalline water-ice, as well as crystalline silicates, in its ISO LWS and SWS spectrum. Cohen et al. (2002) presented the SWS and LWS spectra of more [WCL] PNe showing both strong UIR-bands and strong crystalline silicate features and dubbed them as having 'dual dust chemistries'. A number of interpretations of the dual dust chemistry phenomenon have been considered by the above authors, including (a) a recent thermal pulse that has brought up and ejected C-rich material into an O-rich nebula (the phenomenon appears too frequent however to be consistent with such dredge-up events, which ought to be encountered only rarely); or (b) the presence of comet clouds at large radii, which have been disrupted by the impact of expanding C-rich nebulae, liberating O-rich silicate and ice particles. However, the most likely explanation now seems to be (c) the presence of pre-existing dust disks around binary systems in these objects, which contain O-rich particles that have been captured and stored from previous O-rich AGB evolutionary stages. Self-shielding disks would enable crystalline silicate and ice particles to remain relatively cool, while C-rich particles synthesised during more recent evolutionary events would be channelled towards polar directions. Direct evidence for the presence of optically thick dust disks around dual dust chemistry objects has come from the speckle interferometric detection by Osterbart et al. (1997) of an obscuring disk or torus in the Red Rectangle, and the detection of a similar obscuring disk or torus in CPD–56^{o}8032 by De Marco et al. (2002), from HST STIS optical and UV long-slit spectroscopy.

As discussed in Section 3.2, a strong 21μm emission feature is often detected around carbon-rich post-AGB objects. Its non-detection in the spectra of AGB stars and PNe had led to suspicions that the carrier was a transitory species. Hony et al. (2001) have however claimed the detection of a 21 μm emission feature in the SWS spectra of two PNe having H-deficient Wolf-Rayet central stars, NGC 40 and NGC 6369. Hony et al. (2002b) also reported the detection of a 23 μm emission feature in the SWS spectra of the PNe M 2-43 and K 3-17, which they attributed to iron sulphide, with M 2-43 also showing evidence for weaker FeS features at 34, 38 and 44 μm. M 2-43 has a H-deficient WR central star; the nature of the central star in K 3-17 is not currently known. Harrington et al. (1998) reported the detection of an unusual 6.4 μm emission feature in the SWS spectra of the PNe Abell 78 and IRAS 15154-5258 (PM 1-89), both of which have H-deficient WC central stars. They identified the feature as an aromatic C–C stretch feature produced in carbonaceous grains with little or no hydrogen. It is striking that most of the discoveries discussed above have been associated with PNe that have H-deficient WC Wolf-Rayet central stars, a group that accounts for no more than 15% of all PNe.

NGC 6302 is a much more evolved, high-excitation, PN than the dual dust chemistry [WCL] PNe, with a highly bipolar geometry. Figure 3 shows its continuum-subtracted 2.4–197 μm spectrum (Molster et al. 2001). As well as showing a UIR-band spectrum in the 3–13 μm region (attributed to C-rich particles), longwards of 17 μm the spectrum is seen to be dominated by strong emission features, identified with crystalline silicates and crystalline water-ice (the latter at 44 and 62 μm). There is a very broad feature peaking at about 90 μm in Figure 3, which was not identified by Molster et al., although they suggested that it might be due to hydrous silicates. Kemper et al. (2002b) identified this feature as due to a 92.6 μm band of calcite, $CaCO_3$. They also suggested that dolomite, $CaMg(CO_3)_2$, contributes to the observed 62 μm feature. The interest in the calcite identification is that this material normally requires the presence of liquid water for its formation. Water-ice features are identified in the spectrum of NGC 6302, but a non-aqueous formation route would seem to be required for the suggested calcite component in NGC 6302.

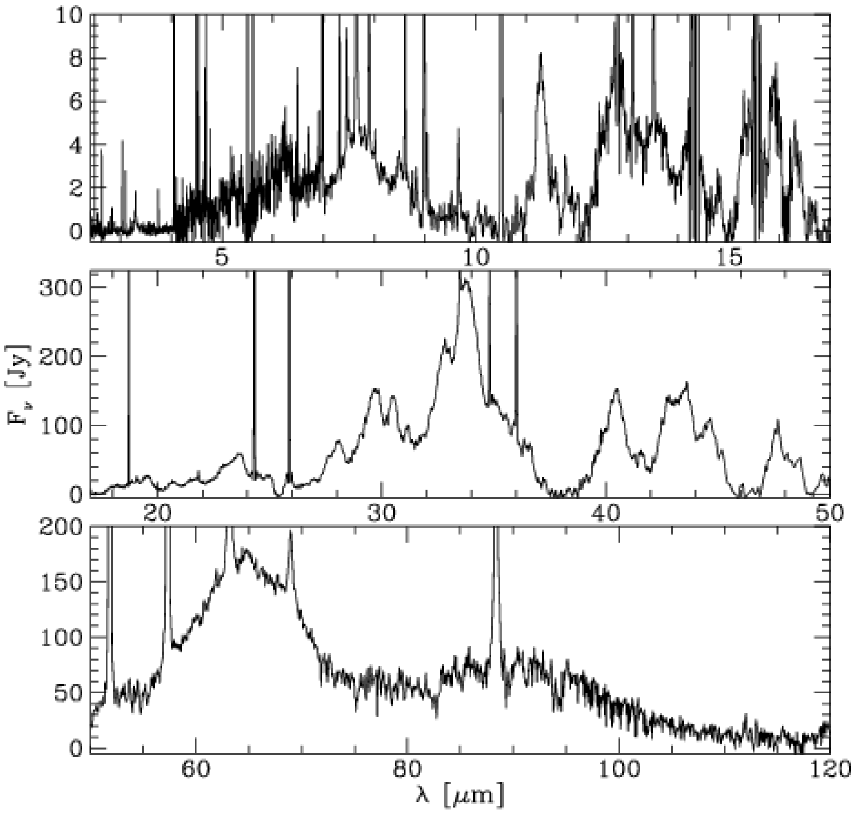

Figure 3. The continuum-subtracted spectrum of NGC 6302 from 2.4 to 197 μm. As well as many ionic emission lines, the 3–13 μm region is characterised by the presence of C-rich emission features, while from 17–80 μm the spectrum is dominated by emission bands attributable to crystalline silicates and crystalline water-ice. From Molster et al. (2001).

The relatively narrow emission feature at 69 μm in Figure 3 has been identified with the crystalline silicate material forsterite, Mg_2SiO_4. Bowey et al. (2001) have shown that the peak wavelength of this feature is a sensitive function of temperature for laboratory particle samples, shifting by nearly one micron as grains are cooled from 300 K to 4 K. Bowey et al. (2002) used these results to derive dust temperatures of 30–140 K from the observed peak wavelengths of the 69 μm feature in the ISO LWS spectra of a range of PNe and post-AGB objects.

4.2. The neutral zones around PN

Many planetary nebulae have surrounding neutral atomic and molecular zones which emit strongly in the ISO spectral range. Their photodissociation regions (PDRs) are sites of active chemistry, allowing a number of transient species to be produced and detected, in addition to the well-known IR lines of CO and H_2. In addition to eleven rotational lines of CO, Liu et al. (1996) reported the detection of the 119.3 μm fundamental rotational line of OH from the PDR around NGC 7027, in a high signal to noise LWS spectrum. They also detected an emission line at 179.6 μm, which they identified with the fundamental rotational line of o-H_2O. However, a re-analysis of the data by Cernicharo et al. (1997) led to the re-allocation of this line to the J=2-1 rotational transition of CH^+, supported by the detection in the same LWS spectrum of the 3–2, 4–3, 5–4 and 6–5 transitions of CH^+, at 119.90, 90.03, 72.140 and 60.247 μm, the first detection of the rotational spectrum of CH^+. Liu et al. (1997) reported the detection in the NGC 7027 LWS spectrum of emission lines at 149.18 and 180.7 μm which matched the wavelengths of CH rotational lines and represented the first detection of the far-IR lines of this radical. Detailed models for the PDR around NGC 7027 have been constructed by Yan et al. (1999) and by Hasegawa et al. (2000) and have provided good matches to the observed LWS rotational line fluxes from CO, OH, CH and CH^+.

Liu et al. (2001) determined the temperatures and densities of the PDRs around 24 PNe, from the observed line intensity ratios of [C II] 158 μm and [O I] 63 and 146 μm, with the deduced temperatures typically falling between 200 K and 500 K and the densities ranging from 10^4–3×10^5 cm^{-3}. With a temperature of 1600 K, NGC 7027 had one of the warmest, as well as one of the densest, PDRs studied.

NGC 7027 is an example of a young, high-density and incompletely ionized PN. Turning to the other extreme of PN evolution, the old, low-density PN NGC 7293 (the Helix Nebula) was imaged by Cox et al. (1998) in the ISOCAM 6.9 and 15 μm filters. Their complementary ISOCAM CVF spectra revealed that the emission in the 6.9 μm image was completely dominated by the S(5) line of H_2 and that no dust continuum or PAH UIR-band emission was detectable. The H_2 line intensity distribution could be fitted by a rotational temperature of 900 K and column densities of $\sim3\times10^{18}$ cm^{-2}, while the total luminosity in H_2 lines amounted to 6% of the central star luminosity, much higher that predicted for PDRs. The H_2 emission appears to originate from the many neutral globules in the Helix Nebula that have been imaged at optical wavelengths and in mm-wave CO lines. Persi et al. (1999) have presented ISOCAM images and CVF spectrophotometry of a further six PNe, ranging from high-density to low-density objects.

4.3. THE IONIZED REGIONS OF PN

Liu et al. (2001) presented ISO LWS [O III] 52- and 88 μm, [N III] 57 μm and [N II] 122 μm fluxes for a sample of 51 PNe. The electron densities derived from the [O III] 52/88 μm flux ratios were found to be systematically lower than those obtained for the same nebulae from higher critical density optical diagnostic line ratios, consistent with the presence of significant density variations within the nebulae, with the [O III] 52- and 88 μm lines (critical densities of 3500 and 1500 cm^{-3}, respectively) being quenched in the higher density nebular zones. However, Tsamis et al. (2004) have shown that for those nebulae for which the IR and optical density diagnostic ratios all indicate electron densities below the critical densities of the [O III] IR lines, the electron temperatures derived from the [O III] λ5007/λ4363 ratio and from the λ5007/(52 μm+88 μm) ratio agree well with each other, ruling out the presence of significant temperature fluctuations in these nebulae, since the IR lines of [O III] have much lower excitation energies than do optical lines such as λ4363.

The SWS spectral region contains many ionic fine structure (FS) lines and a number of papers have been published presenting FS line fluxes and nebular abundance analyses for 18 different PNe (Beintema & Pottasch 1999; Pottasch & Beintema 1999; Pottasch et al. 2000, 2001, 2002, 2003a,b, 2004; Bernard-Salas et al. 2001, 2002, 2003; Ercolano et al. 2003; Surendiranath et al. 2004). These analyses take advantage of the low excitation energies of IR FS lines and thus the relative insensitivity of the derived ionic abundances to the adopted nebular electron temperature. If the particular FS line has a critical density below a few$\times 10^4$ cm^{-3}, i.e. within the typical electron density range for PNe, then the derived ionic abundance is quite sensitive to the adopted electron density, but many FS lines in the SWS domain have critical densities above this range and so make good abundance diagnostics. Marigo et al. (2003) have compared the abundances derived in many of the above-referenced papers to synthetic evolutionary models for the AGB phase, confirming the presence of 'two groups of PNe, one indicating the occurrence of only the third dredge-up during the TP-AGB phase, and the other showing also the chemical signature of hot-bottom burning.'

van Hoof et al. (2000) have used ISO SWS measurements of [Ne V] infrared FS lines to re-assess the accuracy of published collision strengths for the Ne^{4+} ion, concluding that the R-matrix calculations of Lennon & Burke (1994), which had appeared to conflict with some earlier observations, were accurate to at least 30%. Rubin et al. (2002) discussed the observed ratios of a number of density-sensitive FS line ratios falling in the SWS domain and showed that several of the measured ratios for PNe were outside the range predicted using current atomic data (including the [Ne V] infrared FS lines discussed by van Hoof et al.), implying the need for improved atomic collision strengths. Feuchtgruber et al. (1997) used ISO SWS grating and Fabry-Pérot observations of several PNe to measure improved rest wavelengths for 29 infrared fine-structure lines, while Feuchtgruber et al. (2001) provided similar data for a further six FS lines.

5. Observations of novae

Many of the same ionic fine structure lines observed in planetary nebulae can also be observed in the spectra of novae, and ISO spectroscopy of these lines has been able to reveal a great deal of information about the ionized gas component of nova shells. Salama et al. (1996) reported SWS and LWS observations of Nova V1974 Cyg 1992, obtained 1494 days after outburst. From measured FS line flux ratios, they estimated electron temperatures in the ejecta and derived an enhanced Ne/O ratio of $\sim$4. Salama et al. (1997) presented further ISO SWS observations of Nova V1974 Cyg 1992, including detailed line profiles of the [Ne V] 14.32- and 24.32μm lines at four different epochs. The density-sensitive [Ne V] line ratio was found to decrease with time t as t^{-3}, in accord with ejecta expansion expectations. Salama et al. (1997) also presented ISO spectra of Nova HR Del 1967 and Nova V705 Cas 1993. Further ISO observations of the latter nova, obtained between 950 and 1455 days after outburst, were presented by Salama et al. (1999). The [O IV] line at 25.89 μm was found to be strongly in emission. Upper limits to the fluxes of neon FS lines led to an upper limit of 0.5 solar for the Ne/O number ratio in the nova shell.

As well as obtaining observations of older novae, a nova Target of Opportunity programme was carried out during the 1995-1998 duration of the ISO mission, which was combined with co-ordinated complementary ground-based optical and near-IR spectroscopic observations. The ToO programme was unlucky in that no bright dust-forming novae occurred during the mission. However, the novae that were observed produced a rich harvest of information on second and third row elemental abundance distributions with which to compare with explosive nucleosynthesis predictions. Lyke et al. (2001) presented ISO, IUE and ground-based data on Nova V1425 Aql 1995 and combined these with a detailed photoionization model for the evolving nova shell. The mass of the shell was derived to be 2.5–4.3$\times10^{-5}$ $M_\odot$, with the modelling indicating that C and O were enhanced by a factor of 9 with respect to solar, while N was enhanced by a factor of 100 and Ne was only slightly enhanced. The presence of a CO white dwarf in the system was confirmed and a distance estimate of 3.0±0.4 kpc to the nova was obtained.

From their SWS IR and AAT optical and near-IR spectra of the heavily reddened Nova CP Cru 1996, Lyke et al. (2003) derived a distance of 2.6±0.5 kpc to the system. Relative to solar, they derived abundance enhancements for N, O and Ne of 75, 17 and 27, with Mg showing an approximately solar abundance. The enhanced neon abundance but relatively low Mg abundance led them to interpret this object as a 'missing link' between CO novae and ONeMg novae.

Nova V723 Cas 1995 was observed at six different epochs by ISO, from 217 to 805 days after outburst, showing prominent highly ionized coronal fine structure line emission (Evans et al. 2003). From the flux ratios of hydrogen recombination lines having similar wavelengths, they derived reddening-insensitive electron temperature and density estimates, finding $N_e(\mathrm{cm}^{-3}) \sim 2 \times 10^8[250/t(\mathrm{days})]$, where t was the time since outburst. For a distance of 4 kpc, they estimated an ejected shell mass of between 2.6×10^{-5} $M_\odot$ and 4.3×10^{-4} $M_\odot$. No lines of neon were detected, excluding V723 Cas from the class of ONeMg novae and implying that it has a CO white dwarf core.

6. Symbiotic Stars

Symbiotic stars are long-period binaries which generically contain a cool red giant star and a hot, evolved object that produces ionization in the circumstellar outflow. The hot component of the vast majority of symbiotic systems is typically a hot white dwarf orbiting close enough to the red giant that it can accrete material from its wind. There are two distinct classes of symbiotic systems: the S-type (stellar) with normal red giants and orbital periods of about 1 to 15 years, and D-type (dusty) with Mira primaries usually surrounded by a dust shell, and orbital periods longer than about 10 years (Nussbaumer and Stencel, 1988). Symbiotic stars are interacting binaries with the longest orbital periods, and their study is essential to understand the evolution and interaction of binary systems.

IRAS measurements of the brighter symbiotic stars (most symbiotics were only detected with IRAS as mili-Jy sources), indicated the presence of dust shells with characteristic temperatures of 250 to 800 K and dimensions of tens of AU (Anandarao et al., 1988). These warm shells are surrounded by more extended ones which were detected recently in sub-mm wavelengths (Mikolajewska et al., 2002 and references therein). Some symbiotic systems were observed with ISO and the results from the published observations are discussed below. The majority of symbiotics were however too faint for ISO and are in fact ideally suited for the Spitzer Space Telescope.

Preliminary results from ISO observations of symbiotic stars were presented by Eyres et al. (1998b). ISO SWS observations of the symbiotic novae (or very slow novae) RR Tel and V1016 Cyg reveal prominent, broad 10 and 18 μm silicate dust features. In both cases, the 10 μm feature is well fitted by the crystalline silicate feature found in Novae Her 91. There is some observational evidence that the silicate feature at 10 μm show time-dependent variations. In addition, SWS spectra show a number of narrow emission lines, which can be used to constrain abundances.

ISOPHOT observations were made for the S-type symbiotics AG Dra and AG Peg, providing multi-filter photometry and spectrophotometry. The observed emission is dominated by the giant-component continuum. There are some additional features: a broad plateau between 2.47 and 3.0 μm; a broad feature around 3.2 μm (AG Dra) and at 3.8 μm (AG Peg); a clear excess between 10 and 15 μm in both cases. Note, however, that some of these features could be of instrumental origin.

Schild et al. (1998) discussed spectral features in SWS and LWS spectra of CH Cyg. Much of the ISO wavelength range is dominated by the emission of silicate dust with almost no nebular emission lines (at the time of observations the symbiotic activity of CH Cygni was small). In addition, they find strong OH and weak H_2O emission between 60 and 130 μm. Note that OH molecules are absent in spectra of single giants of similar spectral type. Apart from the well known photospheric absorptions of CO (the band heads of ^{12}CO and ^{13}CO are well discernible), OH and SiO, they also tentatively detected traces of HCl and relatively weak PAH features at 6.3 and 11.3 μm. The authors suggested that carbon rich material may be ejected from the outbursting companion.

Schild et al. (2001) presented and discussed SWS and LWS observations of the symbiotic star HM Sge. The emission from this star is dominated by silicate dust with a number of nebular emission lines superimposed on the dust continuum. In the short wavelengths there are no molecular absorption features what suggest presence of warm dust. Analysis of the overall spectral energy distribution of HM Sge allowed to suggest that in addition to a Mira dust shell there is a second dust component associated with the hot source. This second shell is located at the interface between the Mira dust shell and the dust free region carved out by the hot companion. The dust envelope associated with the Mira is very extended and optically thin, whereas the second dust component is geometrically rather thin but dust rich. The general agreement of the presented model with ISO observations suggest that radiation (not collisions) is the main dust heating mechanism.

There are still ISO spectra available (but probably of lower quality than the above discussed) for some symbiotic stars which show many nebular emission lines and can be used together with optical data to better constrain chemical abundances in ionized parts of these systems.

7. Wolf-Rayet stars

Wolf-Rayet (WR) stars represent one of the final stages of stellar evolution for massive stars. In general, they are thought to follow an evolutionary sequence divided into three phases: WN, WC and WO, which correspond to dominant emission lines in their spectra (see van der Hucht (2001) for a review). These emission lines are formed in the stars' hot winds (typical mass loss rates are between 10^{-6} and 10^{-4} $M_{\odot}\,yr^{-1}$) and have velocities in the range between 1000 and 2500 $km\,s^{-1}$. The WR phase is predicted to be brief, lasting only a few 10^5 years before ending in Type II supernova explosions. Despite their harsh environment some WC-type WR stars are known to be surrounded by circumstellar dust (e.g Williams, 1995). Therefore, ISO spectroscopic observations were suitable for both: to study chemical composition of ejected and ionized gas as well as dust spectral features.

Preliminary results from ISO-SWS observations of seven Wolf-Rayet stars were presented by van der Hucht et al. (1996). They discussed Ne and He abundances in WR 11 on the basis of SWS 04 spectra, and dust features in WC 8-9 stars: WR 48a, WR 98a, WR 104, WR 112 and WR 118 from medium resolution SWS 02 observations. Their target stars, except for WR 11, are heavily reddened and SWS spectra show absorptions by silicates and hydrocarbons, possibly of interstellar origin.

Still preliminary results were discussed in more detail during "ISO's view on stellar evolution" conference held in Noordwijkerhout in July, 1997 (Morris et al., 1998, Willis et al., 1998 and Williams et al., 1998). One of the problems considered there was the neon abundance. Stellar evolution models predict an enormous enhancement in surface Ne abundances in WC stars, making it the fourth most abundant behind He, C, and O in the WC stars. Before the launch of ISO, observations suggested that Ne/H is enhanced by a factor of 2 rather then >10 as models predicted (Barlow et al., 1988). This conflict was a major puzzle in WR research. SWS observations of several Galactic WR stars have been obtained to provide tests of this controversy. Analysis of the SWS spectra showed that the neon abundance is rather close to that predicted by stellar evolution models in the cases of WR 146 and γ^2 Vel (WR 11), but rather lower than predicted in the case of WR 135. Surprisingly, an overabundance of Ne was found in a WN8 star, WR 147, and rotational mixing has been proposed as a plaussible explanation. The WN8(h)+B0.5 V binary system WR 147 has been further analysed by Morris et al. (2000). Using SWS data they were able to put constraints on the surface abundances of Ca, S and Ne, which were in a good agreement with the solar values of these elements for the H-depleted environment of WR 147.

A detailed analysis of the Ne abundance problem in WC stars, based on the SWS and ground-based data, was presented further by Willis et al. (1997) for WR 146 and improved by Dessart et al. (2000), who considered also other WC stars: WR 11, WR 90 and WR 135. They estimated that Ne/He = 3–4 10^{-3} in the case of WR 11 and put an upper limit of the same order on the three remaining WC stars. Neon is highly enriched but observed Ne/He ratios are still a factor of 2 lower than the predictions of current evolutionary models for massive stars (see e.g. Maeder, 1991; Meynet, 1999). They also suggested that an imprecise mass loss and distance were responsible for the much greater discrepancy in neon content identified by Barlow et al. (1988). Note, that Smith and Houck (2001) have obtained groundbased mid-infrared (8-13 μm) spectra for a sample of Galactic WR stars which, except for an unresolved discrepancy for WR 146, show agreement with the SWS observations.

It is worth mentioning also the possibility to determine terminal speeds of winds in 3 single WN stars using [Ca IV] 3.207 μm line widths from SWS data for these stars (Ignace et al., 2001). A detailed analysis of these line profiles allowed them also to conclude that the effect of turbulence in the winds of single WN stars is significant. They also showed that the line profile shapes in WR binaries appear asymmetric. In addition, using SWS data, Ignace et al. (2003) were able to put constraints on the velocity law and clumpiness of the wind from the WN-type star WR 136.

As far as dust in H-poor WC stars is concerned, there are two principal questions: how dust is formed near such hot stars and the apparent failure to observe in WR stars any of the expected precursors (such as C-chain molecules) of the C-rich dust. SWS observations of circumstellar dust around Wolf-Rayet stars reveal a variety of spectral energy distributions (SEDs). The mid-infrared SEDs of circumstellar shells around late-WC stars are approximately Planckian, with strong interstellar absorption features (amorphous silicates, CO_2 ice at 4.27 μm, and the 6.2 μm feature to which molecules with the C double bond may contribute). The results of SED modelling by (Williams et al., 1998) allowed them to examine the contributions made by different dust grain types to the observed emission, as well as the relative contributions made by circumstellar and interstellar components to the observed reddening. The authors demonstrated that AC-type amorphous carbon (Colangeli et al., 1995) gave fairly good fits to the observed SEDs.

From pre-ISO observations with the KAO of two dusty WC9 stars, Cohen et al. (1989) had reported the presence of the 7.7 μm but the absence of the 6.2 μm unidentified infrared features (frequently attributed to C=C stretch modes of PAHs), while Chiar et al. (2002) reported the detection of features at 6.4 and 7.9 μm in the ISO SWS spectrum of the dusty WC8 Wolf-Rayet star WR 48a. Since the atmospheres of these stars are H-poor, the detected features are believed to be due to large hydrogen-poor carbonaceous molecules or amorphous carbon dust grains, and not due to PAHs. Interestingly, the features in the spectrum of WR 48a resemble the features observed in the spectra of H-deficient planetary nebulae. These similarities point towards a similar origin for the dust in these H-deficient environments and highlight the apparent sensitivity of the bands to local physical conditions.

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