Mid-Infrared Spectral Evolution of Post-AGB Stars

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Summary. A summary is given of the current knowledge of the overall spectral evolution of the circumstellar material around post-AGB stars up to the planetary nebula phase, with emphasis on the evolution of dust features. There are substantial differences in this evolution for the oxygen-rich and carbon-rich cases. I then highlight how the current and forthcoming *Spitzer Space Telescope* observation are likely to provide much new information about this evolution.

1 Introduction

Rigorously identifying objects that have evolved off of the AGB but have not yet become planetary nebulae (PNe) has been difficult. While a small number of these post-AGB (pAGB) objects were known prior to the *Infrared Astronomical Satellite* (IRAS) mission, much of our current knowledge about post-AGB evolution comes from *Infrared Space Observatory* and other follow-up of IRAS sources. Hundreds of pAGB candidates are listed in the Torun Catalogue by Szczerba and co-workers [6] from work by several groups of people around the world. The majority of these objects represent different selections of IRAS sources, except for halo B-type pAGB objects that most probably are not going to evolve to be PNe.

Several basic results are clear from these observations: (a) some of the best-known post-AGB objects such as the Egg Nebula and the Red Rectangle, plus a number of new objects discovered by IRAS such as HR 4049, have unusual properties and these objects seem unlikely to evolve into a typical PN – hence my explicit use of the term "post-AGB" rather than "pre-" or "proto-planetary nebula" (PPN); (b) while the basic division of objects as being oxygen-rich or carbon-rich is fundamental in their mid-infrared properties, there are a number of things that we do not understand, including objects of mixed chemistry and details of how the dust features evolve in the post-AGB phase; and (c) in the mid-infrared there is a strong overlap in broad-band colours between pAGB objects and PNe. A review of the IRAS results on PPNe is given in [4]. Point (a) above has not been generally appreciated by PN researchers (and caused significant discussion after my presentation at the meeting). The three specific systems named are all binary systems with strong evidence for a long-lived stable circumbinary disk. Thus the rate of evolution of the stars must be very slow so they are unlikely to become hot enough to produce a PN before the circumstellar material has completely dispersed. Many similar, although less extreme, systems exist and these are not the best candidates to become PNe. What is germane here is that post-AGB objects in known binary systems need not automatically be PN progenitors.

2 The General Picture

With the larger sample of AGB stars and candidate post-AGB objects we have been able to gather a consistent picture of the post-AGB spectral evolution by searching for objects with mid-infrared properties similar to those of PNe or intermediate between those of AGB stars and PNe. (For other possible selection criteria see [6].) The conventional wisdom is that much of AGB mass loss takes place very late in the evolution hence the highest optical depth AGB objects (OH/IR stars and their carbon-rich analogues) must be the immediate progenitors of PNe. By looking for stars of intermediate stellar and circumstellar properties between these AGB objects and typical PNe we find the best candidates for PPNe.

From the observations and from dust radiative transfer models we can understand the spectral evolution: as the dust shell expands after the AGB it cools and the optical depth decreases. When the star begins its rapid evolution to high temperature the dust shell may become hotter and interactions with new winds from the star may increase the optical depth somewhat, so there is not a one-to-one correspondence of dust temperature or optical depth with age [8]. Figure 1 shows the general trend of the expected evolution.

It has proven much easier to identify carbon-rich PPNe than oxygen-rich PPNe because the identification of S-process element enhancements gives us direct proof that the star has experienced thermal pulses. For the oxygen-rich candidates this analysis has generally been inconclusive and for many individual objects there is on-going debate about whether they are pAGB stars or massive super-giant stars.

2.1 Oxygen-rich Candidates

A relatively small number of very likely oxygen-rich pAGB stars are known including IRAS 18095+2704, IRAS 171500−322 and HD 161796. These are well-studied objects whose spectral energy distributions (SEDs) have been modeled by different groups. Again in these individual cases the inferred stellar masses tend to be low and there is some doubt that they will evolve fast enough to become PNe. The status of some of the brighter IRAS objects identified as PPN candidates, such as IRAS 19114+0002 and IRAS 10216−5916, is still being debated. Very early in the pAGB when the dust shell optical depth is high many candidate objects – for example the non-variable OH/IR stars – have been identified but verifying the evolutionary status of these objects with abundance analysis is difficult.

The spectral evolution of these stars appears to be fairly well understood in general, although not always in detail. Where the dust shell is hot enough to radiate at 10 μm the amorphous silicate feature is seen, possibly along with weaker crystalline silicate features. Except for the possibility that the crystalline silicate features strengthen in the pAGB phase we do not see much evidence of any changes

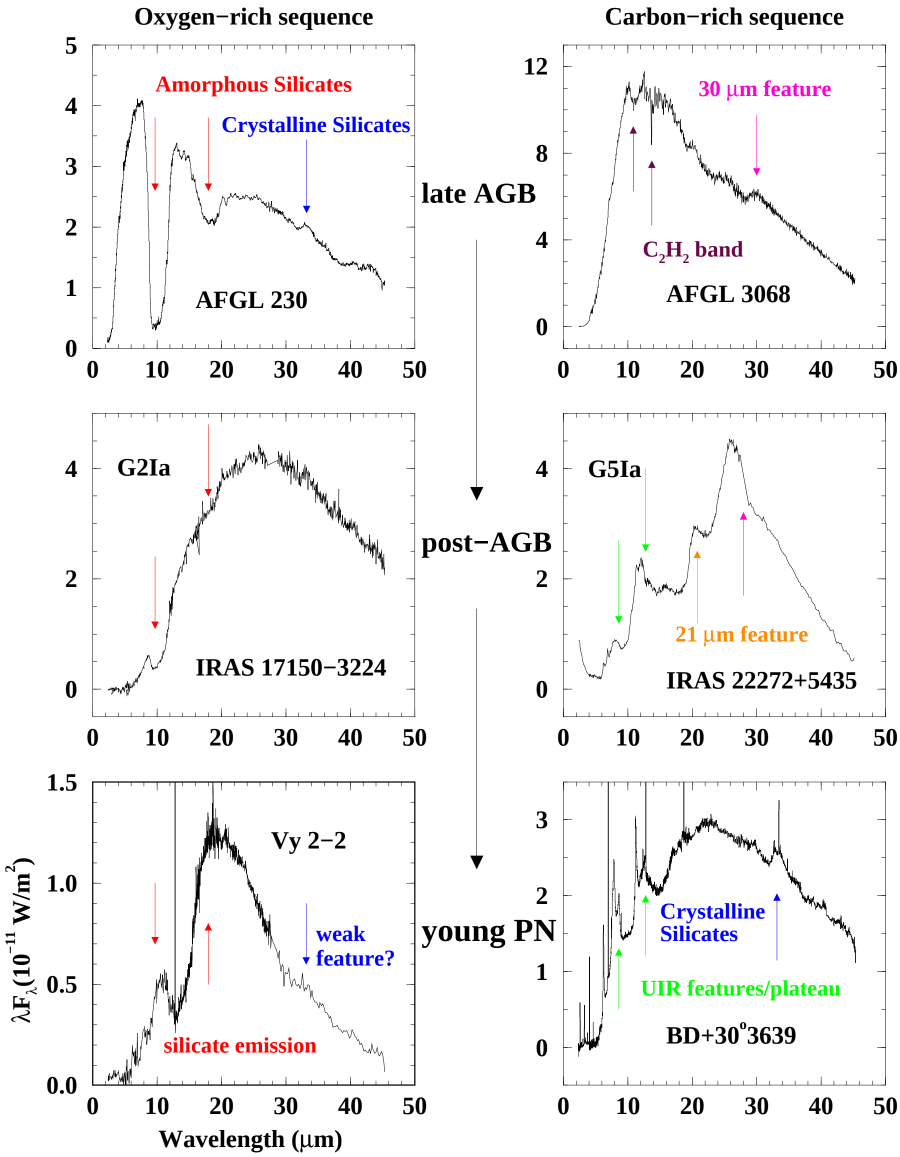

Fig. 1. Illustration of the spectral evolution from the AGB to the PN phase. The oxygen-rich and carbon-rich cases are shown separately. (See the conference presentation for more details.) Note that while the same features are seen through the sequence at left, there is a wide variation in the features seen in the right-hand sequence. BD+30°3639 shows dual chemistry. The colours used to mark the features are red for amorphous silicates, blue for crystalline silicates, green for the UIR features, orange for the 21 μm feature, magenta for the 30 μm feature, and finally maroon for molecular bands. Note how the peak of the continuum moves to shorter wavelengths in the PN spectra compared to the pAGB object spectra just above.

in the spectral features during the pAGB phase. It is interesting to note that where ground-based images exist of these objects the oxygen-rich pAGB stars and young PNe appear to be smaller in angular size than carbon-rich objects of similar N-band brightness. The reasons for this are not currently understood. There may also be a trend to have lower dust continuum temperatures for the oxygen-rich objects than in the carbon-rich objects with the same stellar spectral type; this may indicate that the dust grains have a different range of sizes in the two groups of objects. If the grains are larger in the oxygen-rich case it would explain these observations.

2.2 Carbon-rich Candidates

A fairly large fraction of the bright pAGB candidates are carbon-rich. This implies that mid-infrared luminosity of these objects tends to be higher than for the oxygen-rich objects. Where the stars can be studied spectroscopically we can look for S-process element enhancements to prove that the stars are directly related to carbon-stars, and therefore presumably to the carbon-rich PNe [7]. These objects show many features in their mid-infrared spectra: the 30 μm feature also seen in AGB stars and some PN; the 21 μm feature which is strong in a number of pAGB objects but which is either very weak or absent in both the AGB and PN phases; and the UIR or "PAH" features and associated broad plateau features. The UIR/PAH features of PPNe appear to be different from those observed in PNe, HII regions, or the ISM. It is also noteworthy, but not understood, that some of these objects show none of these features or only the 30 μm feature. As well there is a nearly complete lack of the 11.3 μm SiC feature, which is seen in a large fraction of carbon star spectra, in all post-AGB objects. I know of only three possible cases of the SiC emission feature in pAGB objects (see Figure 2 for one of these), but in all three cases the central wavelength and the feature width are very different than what is observed in numerous carbon stars, which makes this tentative identification quite suspect.

In the most extreme carbon star spectra we observe a number of molecular bands, the most obvious one being the C_2H_2 band at 13.7 μm. From the ISO spectra of carbon stars this band is more and more frequent as the spectra get redder, until in the extreme objects with $H - K$ colours of more than 2.5 magnitudes it is always present. By contrast this band is not seen in any of the PPN candidates of intermediate spectral type – yet there are a few more evolved objects such as AFGL 618 wherein many of these molecular bands are observed. While the column density of these molecules will decline proportional to the optical depth in the pAGB evolution, the complete absence of the 13.7 μm band in the ISO spectra of the younger pAGB candidates is quite puzzling to me. Is the molecule removed by chemical reactions when the star reaches G-type or F-type? Or is it simply photodissociated? Or is the expected decline in column density and excitation temperature sufficient to weaken the band so much that it is undetectable at low resolution? Given the key role of C_2H_2 in chemical networks that lead to PAH molecules this is a very important question.

Many of the brighter carbon-rich pAGB objects and PNe are well resolved by ground-based mid-infrared imaging. There have been a number of attempts to use spatially resolved spectroscopy to detect differences between the carriers of the different features – the UIRs, the 21 μm feature, the crystalline silicates where these are observed. To my knowledge there has been no observation of a separation of the carriers of these different features prior to the formation of an ionized region, after which it is observed that the UIR carriers are found in the photodissociation region rather than in the ionized part of the nebula. Since the number of objects for which this has been attempted is relatively small, in the future it may be useful to attempt this for objects that are known to have unusual mid-infrared spectra.

There are a number of instances of objects which have the UIR features as well as crystalline silicate features in their mid-infrared spectra. There has been much speculation as to the cause of this dual chemistry. One thing that has never been explained is why we do not observe crystalline silicate features along with the 30 μm or 21 μm features (see Figure 1 for example). This may indicate that the UIR carrier can be formed in either an oxygen-rich environment or in a marginally carbon-rich environment that does not lead to these other features. This is another very important matter in view of the wide occurrence of the UIR features in the ISM of galaxies.

3 Expanded the Sample of pAGB Objects

The current availability of the *Spitzer* IRS instrument has allowed us to expand the sample of pAGB objects with high quality mid-infrared spectra. Figure 2 shows such spectra of six carbon-rich pAGB objects. While five of the six objects show the normal set of UIR/21 μm/30 μm features, although with widely varying relative feature strengths, one object shows no recognizable features at all. The feature at 11.4 μm in the spectrum of IRAS 08005−2356 does not match either the SiC feature or the UIR plateaus seen in other AGB or pAGB objects, and it currently has no identification. This on-going work with Bruce Hrivnak will be published in 2008. Given the variability of all these features it will require a statistical analysis of a larger sample of objects to possibly shed light on any interrelations between them. At that point more detailed study of such unusual objects as IRAS 08005−2356 to determine why such objects are odd will be an important avenue of research, but we have to be able to define what is typical before we can define what is odd.

4 Current and Future Prospects

Mid-infrared spectroscopy is essential in the analysis of circumstellar dust shells. Broad-band photometry alone does not distinguish the oxygen-rich and carbon-rich cases for most AGB or pAGB objects (see for example [9] for the case of *Spitzer* IRAC/MIPS photometry). Ground-based follow-up continues to be valuable where the objects are bright or where high spatial resolution is required. Yet for many purposes satellite observations are superior when they can be done, and many valuable observations are being gathered by the IRS instrument.

The IRS follow-up of the GLMP sample of potential young pAGB objects from IRAS, as reported by D. A. García-Hernández at this conference is giving us valuable information about a complete sample of candidates. See her talk for many examples of the types of features discussed in this review, especially for the diversity of the carbon-rich pAGB candidates. Along with the optical/near-infrared spectroscopic follow-up reported by P. García-Lario at this conference we are getting to point where we have statistically useful samples of candidate objects, and can start separating the groups by mass and by galactic population. There is still the problem that the distances to these objects are generally poorly known, although in principle the detailed spectroscopic analysis gives independent distance estimates.

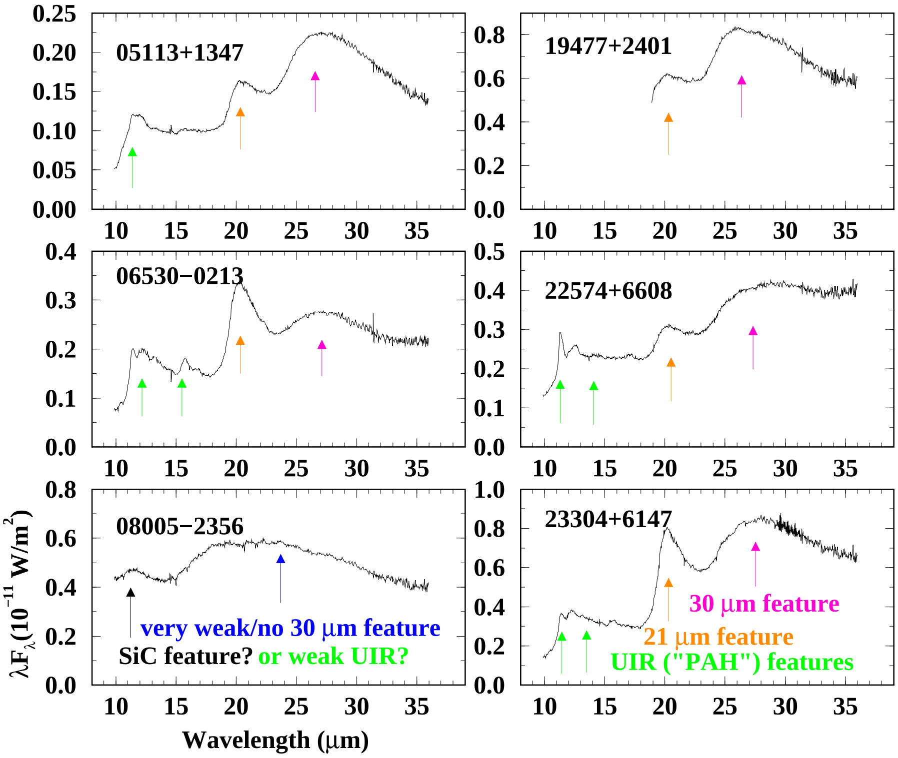

Fig. 2. *Spitzer Space Telescope* IRS spectra of six pAGB stars known to be carbon-rich and to have S-process element enhancement. The various features commonly seen in carbon-rich dust spectra are marked. With the exception of IRAS 23304+6147 all of these are the first good quality spectra obtained at these wavelengths. The 21 μm feature is found, as expected, in four of the objects. From work with Bruce Hrivnak, in preparation.

I wish to highlight the spectroscopic follow-up of specific objects in the Large and Small Magellanic Clouds and its value for understanding post-AGB evolution, since all post-AGB objects in these galaxies should be detected. The SAGE survey [5] of the LMC has detected all stars of K-type or later and luminosities in excess of 1000 $L_\odot$. The equivalent SMC survey will be carried out in 2007/2008 and have similar sensitivity. Since these galaxies are at known distances systematic study of the pAGB objects in these systems can be done in absolute terms and with a complete sample. Despite the excellent work led by P. García-Lario mentioned above we have no prospect of doing the same for the disk of the Galaxy, even when the GAIA mission is completed, since many of the objects we are interested in are heavily obscured and the distances will remain uncertain for these objects.

There have already been *Spitzer* spectroscopic observations of various AGB and pAGB objects in both galaxies, and already some interesting differences have been seen compared to known objects in the Galaxy. One result of this is that it is not possible to produce good models of the SEDs of individual objects without doing work to characterize why and how the dust shells of objects in the clouds differs from objects in the Galaxy. Some preliminary results indicate that carbon-rich objects in the LMC have much stronger molecular bands and weaker 30 μm features than galactic counterparts. Nor have we observed the 21 μm feature in any object beyond the Galaxy. Recent papers ([1], [2], and [3]) highlight some of these differences. Most of the IRS spectra of bright dusty LMC/SMC oxygen-rich objects published to date have been for supergiant stars, as can be readily determined from the total luminosity, and so right now we have less information about oxygen-rich AGB or pAGB objects in the clouds.

Work is ongoing by several groups to identify pAGB objects in the SAGE data. A number of these will be subject to ground-based or IRS spectral follow-up within the next year. The selection of pAGB candidate objects can then easily be extended to the SMC once those observations are taken. It will be of interest to see what the resulting populations actually look like, and what the relative numbers of PNe and pAGB objects is found to be.

5 Conclusion

There are clearly many unresolved questions about the spectral evolution of pAGB objects. The lack of good distances is a fundamental limitation for much that we would like to do. Some unresolved questions are closely related to the difficulty of firmly identifying the carriers of the features that we see in the spectra, and others have to do with the role of molecules and chemistry in the circumstellar envelope (which I have only alluded to for C_2H_2 due to lack of space). Thanks to *Spitzer* the quality and quantity of the mid-infrared data available is improving rapidly to the point where we are starting to have viable samples for statistical purposes both in the Galaxy and in the Magellanic Clouds. My opinion is that the whole field of study needs to move away from the detailed observation of the most famous objects – although that is still valuable – and carefully study the larger samples. It has been clear for a long time, for example, that NGC7027 has a much more massive dust shell than do most PNe. So while it is the most studied PN it should not be taken as typical. We need to work to eliminate the same types of biases in the study of pAGB objects. It is useful to study the Red Rectangle, which appears to be unique in the Galaxy, but we should not use it as an example of a typical pAGB object. Some very unusual new objects have been found by *Spitzer* IRS observations (i.e. [1], [3]). While we study these stars to find out why they are unusual, we have to remember that they probably represent a tail of the total population and not lose sight of establishing what is typical. The photometric survey capability of *Spitzer* is providing us with unique new data sets for the study of the dust shells of AGB and pAGB stars both in our Galaxy and in nearby systems, which will be a challenge to interpret properly.

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