CARBON- AND OXYGEN-RICH PROGENITORS OF PLANETARY NEBULAE

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1. Introduction

This review concerns stars on the Asymptotic Giant Branch that are about to develop into planetary nebulae (=PNe). They are still termed "stars", and properly so, and yet they have already, in statu nascendi, the structure of a PN. There are two different kinds: oxygen-rich stars (spectral class: M) and carbon- rich stars (spectral class: C).

There is, we estimate, a consensus that AGB stars are immediate progenitors of PNe. The frontier of present day research is thus beyond the status of the AGB stars and concerns the next generation of questions: How do AGB stars make the transition? What mechanism inside the stars is the main cause? However, to have a firm beginning it seems useful to summarise in Section 2 the main arguments for our confidence in the AGB stars as progenitors of PNe.

For an introduction into this topic we strongly recommend the proceedings of a meeting in 1989 in Montpellier (France): "From Mira to Planetary Nebula: Which path for stellar evolution?" (Mennessier and Omont, 1990)

2. AGB Stars: The Progenitor Stars of Planetary Nebulae

In 1956 Shklovskii proposed that the core of a red giant might become first the central star of a planetary nebula and later a white dwarf. Several arguments argue convincingly for Shklovskii's proposal: **1.** Calculations of the evolution before and on the Asymptotic Giant Branch (AGB) produce stellar models with a remarkably sharp distinction between a small core of very dense, degenerate matter (very similar to a white dwarf) and a huge envelope with a very low density: core and envelope contain (at least early in the AGB phase) comparable amounts of matter, and yet the core radius is of the order of 10^{-4} of that of the envelope and thus the density in the core is of the order of 10^{12} times that in the envelope. Qualitatively the situation is very similar to that in a PN. **2.** Quantitatively there is also agreement: According to the model calculations the star will, for most of its time, burn quietly hydrogen into helium at a luminosity that is a linear function of the mass of the core (the "Paczynski relation"). From the observed luminosities of AGB stars in our Galaxy ($3000 \lesssim L_* \lesssim 20,000 L_\odot$) one concludes that the masses of the AGB cores range between 0.51 and 0.83 $M_\odot$. This range is very similar to that of white dwarfs and of the central stars of PNe (Weidemann, 1990). **3.** An important category of AGB stars are the OH/IR stars. These stars have a galactic distribution that is remarkably similar to that of the PNe: not only is there close similarity between the two distributions in the plane of the sky (the l-b diagram) but also in the characteristic distributions of longitude versus radial velocity (the l-V diagram).

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One concludes that PNe and OH/IR stars both belong to the "old disk" population and thus both come from the same main sequence stars.

Originally Shklovskii's proposal posed one major difficulty: A planetary nebula contains less ionized gas than the original envelope- a conclusion that is confirmed again at this conference (original envelope mass between 0.4 and several time $M_\odot$; ionized mass between 0.01 and 0.2 $M_\odot$). Yet this does not longer pose a serious objection against Shklovskii's proposal because: **4.** In young open clusters with turn-off masses of a few times $M_\odot$ white dwarfs have been detected of mass less than 1.0 $M_\odot$ (Weidemann, 1990). This informs us that the envelope is largely ejected, but it does not tell us why and how this happens. **5.** AGB stars have been discovered that expell their outer layers at a rate of the order of 1 $M_\odot$ in 10^4 to 10^5 year: infrared stars; OH/IR stars and C-stars like IRC+10216. The discovery that high mass-loss rates exist is necessary, but not sufficient evidence; at present we have no generally accepted proof that this high mass-loss phase lasts sufficiently long, and yet there seems to be a consensus that it does; the point will be discussed further down. **6.** Haloes of neutral material have been found around the ionized gas of PNe, and those may contain the envelope mass (see especially the work by Balick et al., 1992, and this symposium).

3. Samples of AGB Stars

3.1. IN THE MAGELLANIC CLOUDS

The LMC and the SMC offer the possibility to study stars all at the same distance and statistical properties of complete samples may be discovered. A disadvantage is their distance: m-M=18.47 for the LMC and 18.6 for the SMC. Over the last ten years much research has been done on AGB stars in the Magellanic Clouds. We list some developments.

1. The study of field stars in the LMC (Reid and Mould, 1984) and in the SMC (Reid and Mould, 1990). The authors conclude that the observations contradict predictions from earlier model calculations (e.g. Renzini and Voli, 1981). The Paczynski relation (mentioned above) predicts $M_{bol} = -7.1$ if the core mass equals the Chandrasekhar limit. One expects quite a few stars near that limit, but in fact there are few stars with $M_{bol} < -6.0$. Reid and Mould suggest that in these early model calculations the importance of mass loss has been underestimated.

2. The study of AGB stars in clusters. The Magellanic Clouds contain many stellar clusters, and the ages of these clusters spread very nicely over the range from 10 Myr to 10 Gyr - unlike the situation in our Galaxy where the clusters are either very young (< 1 Gyr) or very old (15 Gyr). Because AGB stars are of intermediate M_{ms} and intermediate age, they can be found in most Magellanic Cloud clusters. A recent paper, also a summary, of much work done on individual cluster stars is by Frogel et al. (1990); they discuss 39 clusters and about 400 AGB stars. The work shows clearly that younger clusters produce brighter AGB stars. In the LMC carbon stars occur in clusters with an age between 0.1 Gyr and a few Gyr; in the SMC carbon stars occur even in the oldest clusters. For the LMC one concludes that stars with M_{ms} below 3 to 5 $M_\odot$ become carbon stars when they

reach a certain, high luminosity during their climb along the AGB.

3. Recent deep searches for LPV's in the LMC have been made by Reid et al. (1988) and by Hughes (1989). See also the discussion by Hughes and Wood (1990). More than 1000 LPV's were found, half of them SRa and half Mira variables. The distribution of the pulsation periods shows one strong peak at about 200 days, a sharp downfall for shorter periods and a more shallow fall-off for longer ones. This peaked distribution strongly resembles that for Mira variables in the solar neighbourhood except that for the local Miras the peak is shifted to somewhat longer periods. A specific problem in understanding the results is the total number found: on various grounds Hughes and Wood argue that about 15 times more Mira's should be expected. This, they argue, points to a fundamental lack of understanding; perhaps an AGB star is an LPV star for less than 10% of its time. A point not noted by Hughes and Wood, is that the luminosity distribution of their LPV sample is very similar to that of the field AGB stars found by Reid and Mould (1984).

4. The studies mentioned sofar all started with photographic studies, usually in the I band. We know however that in our Galaxy the AGB stars sometimes eject matter (especially true for the LPV's) and that they are then very reddened. To find them you have to search in the infrared, and preferentially beyond 3 μm. In the Magellanic Clouds, the IRAS survey is of little help: Even heavily obscured stars were faint to IRAS, and in addition the poor angular resolution (several arcminutes) leads to confusion. Nevertheless several studies have been undertaken: Reid et al. (1990) (followed by Reid, 1991) and Wood et al. (1992). Stars with strong circumstellar shells have been found, and in 5 of them Wood et al. detected the 1612 MHz OH maser; these stars are the brightest AGB stars, with $-6 \lesssim M_{bol} \lesssim -7$. It is clear that many more highly reddened objects must exist in the LMC and have not yet been detected (see the next review paper by Whitelock).

These studies of AGB stars in the Magellanic Clouds allow us to get good statistics, i.e. a reliable luminosity distribution, and an insight of what AGB stars become carbon-rich. The scarcity of AGB stars brighter than $M_{bol} = -6$ suggests that the final stages of AGB stars are not determined by nuclear processes around the core but rather by mass loss processes near the surface of the stars: AGB stars bleed to death, before they can explode.

3.2. IN THE GALAXY

AGB stars in our Galaxy are obviously much closer by and can be studied in more detail. Yet, the study of the statistical properties of samples of AGB stars is hindered by the difficulty of determining individual distances. This difficulty plays less a role if one studies stars at about the same distance, e.g. at the galactic centre or in the bulge. Here the problem is of course interstellar extinction. Luckily there are a number of windows; for a large piece of work by a team of several astronomers see a recent paper (Terndrup et al. 1991). Here we will discuss briefly a very recent study by ourselves.

The so-called Palomar-Groningen Field #3 ($l = 0°$, $b = -10°$) -an area of roughly $6.5° \times 6.5°$ for which the extinction is small and well known- has been searched for long period variables and for RR Lyrae stars on B- and R-plates by Plaut (1970) (recently Wesselink (1987) upgraded the results somewhat). These samples can be complemented with a sample of AGB stars with thick circumstellar shells by using the IRAS Point Source Catalogue. This is the subject of a thesis by one of us (J.B.) (to be completed in the autumn of this year; related, earlier studies are: Whitelock et al. 1991 and van der Veen and Habing, 1990). Blommaert concludes that the samples of optically detected Mira variables and the IRAS sample agree so closely in their average luminosity and in the distribution of their luminosities, that both samples must originate from the same parent population of main sequence stars. Because the stars in the IRAS sample have significant longer pulsation periods (on average 450 days against on average 250 days for the optical sample) they must be further evolved: their envelope mass has decreased. Their evolution has been dominated by mass loss, not by core growth.

4. Mass Loss - a New Evolutionary Scenario

4.1. OBSERVATIONS AND MODELS OF CIRCUMSTELLAR SHELLS.

Following the publication of the IRAS Point Source Catalog, and stimulated by vastly improving facilities for millimeter and near-infrared observations a large number of measurements of circumstellar emission have been made over the last 10 years. An excellent compilation of maser observations of more than 3000 stars (with close to 1000 succesful detections) is the one by Benson et al. (1990), and a similarly impressive compilation of 1069 CO line observations of 384 circumstellar shell stars by Loup et al. is in press.

Once again, the distinction between continuum and line observations is useful. Continuum observations, from a few μm to mm wavelengths measure the solid particle distribution, molecular lines (sometimes the 21-cm line) measure the gas; the spectral line also gives the outflow velocity, an item of great importance in the interpretation. To start with the continuum observations: if you want to read up on the topic then for silicate grain models start with Justtanont and Tielens (1992) and for shells containing carboneous grains with Griffin (1990) or Chan and Kwok (1990). These papers show that the modelling has become a well established technique, and that the observed continuum over the full range from 1μm to several mm is explained by basically a simple, spherically symmetric model. Once the expansion velocity, V_{exp} has been derived from spectral line measurements, a fair measurement of the mass loss rate of the dust can be obtained; Justtanont and Tielens compare several different ways to make such estimates (see also the review by Van der Veen and Olofsson in Mennessier and Omont, 1990).

Molecular line emission concerns maser transitions and thermal transitions. We will not dicuss here the maser transitions, although much interesting work on this topic has been done; a recent textbook (Elitzur, 1992) and the proceedings of a recent symposium (Astrophysical Masers (Washington), eds. Glegg and Nedoluha) will have to help you out. Thermal line emission is always observed at millimeter and submillimeter wavelengths. Over the last 5 years or so these measurements have become easier, more sensitive and more reliable. The analysis of the observations is again usually done with spherically symmetric models of continuous outflow.

Such models are increasingly complex, but incorporate also more (and still reliable) physics- for two recent papers see Sahai (1990) and Kastner (1992).

4.2. THE IRAS 2-COLOUR DIAGRAM.

A useful tool to study the properties of circumstellar shell sources is the IRAS 2-colour diagram: a diagram of the $12\mu m/25\mu m$ versus the $25\mu m/60\mu m$ flux density ratio. Van der Veen and Habing (1988) defined areas in this diagram that contain a significant concentration of different types of objects (C-rich stars; Mira's; OH/IR stars; PNe; etc.). These definitions have been found useful. An important addendum to their discussion is a recent paper by Omont et al. (1992) on the locations of carbon stars. Two parameters determine the spectrum and thus the position of an object in the 2-colour diagram: the optical depth of the dust, τ, and r_0, the inner radius where the dust forms. In the 2-colour diagram a well defined curve indicates the position of a star that would gradually increase its mass loss rate and thus the optical depth in its shell (Rowan-Robinson and Harris, 1983; Bedijn, 1987). Actually there are two curves: one for carbon rich dust, the other for silicate dust.

If the mass loss remains constant for more than a few thousand years the object will occupy a definite position on these curves in the 2-colour diagram. If the mass loss stops, the existing shell will expand, the inner radius becomes larger and the object will describe a "loop" through the diagram (Willems and de Jong, 1986). These loops have been invoked to explain why so many carbon stars appear to have normal stellar colours between 12 and $25\mu m$, but a large excess at $60\mu m$; these stars suffered a high mass loss rate, but some 10,000 yr ago the mass loss rate stopped on a short time scale: as a witness of past events the star has still a "detached, fossil shell" around it. Egan and Leung (1991) have confirmed this conclusion by an accurate analysis of the $60\mu m/ 100\mu m$ IRAS colours of carbon stars.

Recently Zijlstra et al. have analysed the IRAS colours of large samples of known M-giant stars and of known carbon stars. They show (a) that all carbon stars are loosing mass heavily, or have finished such a phase at most 10^5 yr ago and (b) that a small, but significant fraction of the M-giants have also old shells around them. Earlier Olofsson et al. (1990) had found detached shells around carbon stars from millimeter line measurements, and they concluded that carbon stars are capable of interrupting the mass-loss process, even when the rate is high, and then later start again (a phenomenon they tried to link with the thermal pulses); Zijlstra et al. conclude that also M-giants on the AGB show this interruptive mass-loss behaviour.

4.3. THEORY OF MASS-LOSS.

Understanding the evolution of the AGB stars implies understanding mass loss. Yet major questions like: "What causes the star to eject matter?"; "How will the mass loss rate develop in time?"; "Is the envelope lost in a smooth, steady proces, or is the proces intermittent and sometimes interrupted?" have today been answered only tentatively. Nevertheless- even a tentative answer is much more than none at all, so we have seen considerable progress. For a good discussion of the problem we refer to the review by Hearn in Mennessier and Omont, 1990.

A promising modelling development is by Bowen and Willson- see their most recent paper in 1991. Mass loss is a two stage proces: because of the stellar pulsations the atmosphere of the star is very extended; this brings enough matter to such a height that solid particles begin to condense; these particles are being driven out by light pressure and carry the gas along. The mass loss rate is essentially determined by the density of the gas at the point where the condensations take place. The resulting outflow velocity depends on how much momentum is transfered by the stellar light. The mass loss rate increases until the envelope gets so thin that the photosphere begins to contract and the star becomes a protoplanetary nebula. Most of the considerations of Bowen and Willson had already been formulated semi-intuitively by Bedijn (1988).

Bowen and Willson attach little significance to the thermal pulses- in their view these are only a temporary interruption. Wood and Vassiliadis (1992) however think that the thermal pulses play a major role: each thermal pulse initiates a period of stellar oscillations, the star becomes a Mira variable for a short time and, because of the pulsations, it loses mass at a high rate. Following every next thermal pulse more mass is lost until finally the matador pulse appears and the bull is being slaughtered: the star becomes a planetary nebula, the feast can begin and the steak can be fried.

Weighing Bowen and Willson's model against that by Wood, it seems that the first has more hydrodynamic modelling to it, but that the observations prefer the second model: mass loss may well be intermittent and not continuous. Apart from the arguments presented by Zijlstra et al. and by Olofsson et al. there are also the following considerations: (1). In the LMC the luminosity distribution of the LPV's agrees closely with that of the non- variable AGB M-giants. This might suggest that the Mira phase appears at one or several intermediate moments, and not as the final stage of the M-giant evolution. (2). Interrupted mass loss may also explain why there are so few Mira's in the LMC and in the solar neighbourhood in comparison to the number of PNe (see Wood's review in Menessier and Omont, 1990).

5. Carbon Rich stars: a difficult group

The first carbon stars were recognised in optical spectra before the turn of the century. More recent are the discoveries of dust-enshrouded carbon stars like IRC+10216. For a recent compilation see Groenewegen et al. (1992) or the discussion by Omont et al.(1992). A difficult question is that of the luminosity distribution; in the Galaxy we do not have the means to obtain a direct determination of distances. Work on carbon stars in the Magellanic Clouds (Frogel et al., 1990) indicates that the distribution of luminosities there is narrow (standard deviation less than 0.50 magnitude), but in the LMC the distribution shifts systematically with the age of the cluster in which the stars have been observed and a comparison between various environments (see e.g. Lequeux in Mennessier and Omont, 1990) reveals large differences between metal-poor galaxies, like the SMC and a metal-rich environement, like the galactic bulge. There is, we think considerable uncertainty about the luminosities of the galactic carbon stars.

The origin of the carbon-richness was felt to have been understood with the discovery by Iben (see his review of 1991) that in the interior of AGB stars, after a thermal pulse newly produced carbon may be added to the (hydrogen) envelope; a M-giant then turns into a C-star when the carbon abundance exceeds that of oxygen. This theoretical result appears to be robust, but there remain major problems with detailed model predictions of when and what stars turn into C-stars (Lattanzio, this symposium). The carbon stars detected in the Magellanic Clouds are all rather bright with an average lumonosity around 8000 $L_{\odot}$, or $M_{bol} = -5$. But in the bulge of our Galaxy carbon stars of much lower luminosity (M_{bol} >-2.5) have been found (see Westerlund et al., 1991). These stars may never have been AGB stars and their carbon richness probably has another cause than a dredge-up after a thermal pulse. More enigmatic carbon stars are the two with thick circumstellar shells found at high galactic latitude (Cutri et al., 1989). Are these true halo objects, or are they escaped members of the galactic disk population? A few planetary nebulae in the halo, most of them carbon-rich, may pose the same riddle (Clegg et al., 1987).

Progress in this field will be difficult to obtain in view of the inability of the observers to provide reliable luminosity functions of carbon stars inside our own Galaxy, and the difficulties that the modellers have in calculating the details of the dredge-up.

6. Last Remarks

That PNe originate from AGB stars appears to be an hypothesis with many solid arguments in favour of it and no solid arguments against it. Yet, we know that the cause, the duration and the time behaviour of mass loss is incompletely understood and we realize that this process is essential for the evolution of AGB stars. About the identification of the bright M-giants and LPV's as AGB stars there is no uncertainty: solid spectroscopic evidence exists of dredge- up phenomena and thus of the existence of thermal pulses. Thus the origin of PNe is largely understood, be it not in detail.

Yet, this success should not close our eyes for the short comings in the present theory: notably on the question of why and how a red giant begins to loose mass when it becomes pulsational unstable; and that while the AGB may provide most of the progenitors, there still may be progenitors of a different breed: the carbon stars in the galactic centre and in the galactic halo seem to tell us that. Common envelope evolution in double stars (read the beautiful review by Iben, 1991) is perhaps part of an alternative way of evolution.

Of the later stages of stellar evolution we may have seen much of the light, but we have not yet seen it all.

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