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Evolution of low mass stars: AGB to PN

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Abstract. The evolution of low mass stars from the AGB to PN stage is described. From the analysis of IRAS data we now know several post-AGB/proto- planetary nebulae that occupy the region in the H-R diagram between the tip of the AGB and planetary nebulae. The K,G,F,A and B post-AGB supergiants form an evolutionary sequence in the transition region evolving from the tip of the AGB to young planetary nebula phase. Multi-wavelength study of these stars and their circumstellar shells is yielding valuable clues to understand their evolution, nucleosynthesis, mass loss, and mixing during AGB to PN stages.

The post-AGB stars with 21 micron emission are found to be metal-poor and over abundant in carbon and s-process elements indicating that they have gone through the third dredge-up and carbon star phase on the AGB. Few 21 micron emission post-AGB supergiants seem to have over abundance of Li and Al. Further detailed abundance analysis of post-AGB stars with 21 micron emission may provide clues to understand the s-process nucleosynthesis, third drege-up and hot bottom burning.

The study of hot post-AGB stars reveals that Hen 1357 (SAO 244567) was a post-AGB B supergiant in 1970 and it has turned into a planetary nebula within the past 20 years. The IUE UV flux of the central star of Hen 1357 has faded by factor 3 within the past eight years indicating that it is rapidly evolving into a DA white dwarf.

1. Introduction

Stars with masses in the range of 0.8 solar mass to 2.3 solar mass are defined as low-mass stars. They develope an electron-degenerate helium core immediately following the main sequence phase. Stars in the mass range more than 2.3 solar mass and less than 8 solar mass are defined as intermediate-mass stars. The intermediate mass stars ignite helium non-degenerately, but develope an electron-degenerate carbon-oxygen (C-O) core following the exhaustion of helium at the center. The low mass stars also develop an electron-degenerate (C-O) core after the exhaustion of central helium, and their subsequent evolution is similar to that of intermediate-mass stars. This phase of evolution of low and intermediate mass stars is called the Asymptotic

Giant Branch (AGB) phase of evolution (it is called AGB since, for low mass stars the evolutionary track in the H-R diagram approaches that of the first giant branch). A detailed review of the AGB evolution and beyond is given by Iben and Renzini (1983) and Iben (1985).

2. AGB stars

During the AGB stage of evolution an AGB star can lose more than half of its initial mass. Therefore the spatial distribution of these stars traces out both the distribution of stars in the Milky Way and an important source of new interstellar matter. The AGB stars have luminosities in the range of 10,000 to 3000 solar luminosities (Iben and Renzini 1983) and therefore they can be detected even if they are very far away. The effective temperatures of AGB stars is less than 4000K and therefore they are late-type stars and mostly radiating in the infrared. The mass loss and circumstellar dust envelopes are common on the AGB. Therefore the infrared surveys (Two Micron Sky Survey, Infrared Astronomy Satellite IRAS point source survey) have provided us the data for a systematic study of the AGB stars and their dust envelopes. Multiwavelength observations of AGB stars, post-AGB stars, and planetary nebulae in the UV, optical, infrared, millimeter wave region and at radio wavelengths have enabled us study the evolution of low and intermediate mass from the AGB to planetary nebula (PN) stage.

In the evolutionary models the location of AGB stars on the H-R diagram is computed. However, observationally it is not always easy to segregate various types of AGB stars. We need their effective temperatures, luminosities, chemical composition etc. We may miss to recognise significant fraction of AGB stars, particularly those in the early AGB phase before the thermal pulsing has started. From the IRAS two colour diagram and from the near infrared color-color diagrams and from objective prism spectral surveys large number of AGB stars have been discovered during the past 10-15 years. The N-type carbon stars, the S-type stars, and Mira variable stars (both oxygen rich and carbon-rich), OH/IR stars are some of the most common types of AGB stars. With modern infrared techniques carbon stars are easily detectable at more than 100 kpc from the Sun.

From the characteristics of optical spectra, dust shells the AGB stars are divided into two groups. The carbon-rich AGB stars and the oxygen-rich AGB stars. This carbon-rich and oxygen-rich grouping also exits in the post-AGB stars and planetary nebulae central stars. The oxygen-rich AGB stars and carbon-rich AGB stars are both characterized by strong molecular absorption bands. M giants with oxide bands and the R and N type stars with carbon-molecules. In oxygen-rich AGB stars the oxygen abundance is more than that of carbon. In carbon-rich AGB stars the abundance ratio of C/O can reach values more than 1. A similar situation also exists in the circumstellar matter around AGB stars. There are AGB and post-AGB stars with carbon-rich dust shells and also there are AGB and post-AGB stars with oxygen-rich dust shells. The oxygen-rich AGB stars appear to populate a small strip in the IRAS color-color diagram (Van der Veen and Habing 1988) indicating continuous distribution of mass loss rates with silicate dust. The carbon stars in the IRAS two color diagram are found over a much larger area than the oxygen-rich stars (see Habing 1990).

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3. Dredge-ups

From the point of view of comparison with the observations the chemical composition changes that occur due to mixing prior to the AGB phase are also important. These changes are brought about when the base of the convective envelope extends inward to "dredge up" matter that has experienced hydrogen burning during preceding phases. During the first dredge-up episode which occurs in all the stars that become red giants for the first time following the exhaustion of central hydrogen there will be changes in the surface composition. As a result of first dredge-up the surface abundances of C,N,Li,Be, and C12/C13 undergo changes. The N (nitrogen 14) abundance on the surface is doubled and the C (carbon 12) abundance is reduced by 30 percent and the C12/C13 ratio becomes about 20 to 30. The surface abundances of Li and Be are reduced by several orders of magnitude. However there is no change in the photospheric abundance of oxygen as a result of first dredge-up.

The second dredge-up phase accompanies the formation of an electron degenerate core following the exhaustion of central helium. In the dredged up matter which can be as high as one solar mass in the most massive intermediate-mass stars, hydrogen has been completely converted into helium and both carbon (C-12) and oxygen (O16) have been converted almost completely into nitrogen (N 14). Thus, only the most massive intermediate-mass stars experience a change in surface composition as they settle onto the AGB. This contrasts with first dredge-up phase when every star that becomes a giant experiences a change in surface composition after hydrogen exhaustion in the center. Thus the magnitude of surface composition changes as a consequence of the first and second dredge-up episodes in a single star are : if the initial composition of CNO elements is in the ratio (C:N:O) (initial) = 1/2:1/6:1 in the units of the initial oxygen abundance (C+N+O = 5/3). During the first dredge-up phase the CNO abundances become (C:N:O = 1/3:1/3:1) nearly independent of stellar mass. For the most massive intermediate mass stars which experience second dredge-up the final abundances of CNO elements are C:N:O = 0.29:0.52:0.86.

For stars of sufficiently large core mass (about 0.7 solar mass or more) and sufficiently large total mass (initial mass more than 2 solar masses) the thermal pulse or helium shell flash approaches limiting strength, the base of convective envelope extends into the region containing highly processed matter. The resulting mixing of freshly synthesized carbon (C12) and neutron-rich isotopes to the surface is called the third dredge-up. When third dredge-up and envelope burning processes are simultaneously active, enormous variations in the surface abundances are generated in the course of the AGB evolution. The over abundance of carbon and s-process elements in the carbon stars and related carbon-rich AGB stars is an observational evidence for the third dredge-up.

4. Mass-loss

AGB stars lose mass through slow and fast winds. At some stage they experience super wind type of mass loss and suffer severe mass loss. AGB stars also undergo radial pulsations. The AGB phase is terminated by severe mass loss. The removal of the outer H-rich envelope through fast mass loss in a short time scale is thought to be responsible for ending the AGB phase for the formation of planetary nebula. The evolution of carbon-rich AGB and oxygen-rich AGB stars is very much influenced by the mass loss and the rate of mass loss. From the IRAS data and from the CO millimeter wave observations and from the OH maser observations it is now well established that the circumstellar dust envelopes and molecular envelopes around AGB stars, post-AGB stars and planetary nebulae are the result of severe mass loss. Amount of circumstellar matter around these objects in the form of dust, gas and molecules cannot be accounted by slow mass rate or Reimers mass loss rate. Mass loss rates ranging from 10^{-7} to 10^{-4} solar masses per year have been detected from the observational data. Most AGB stars experience a phase of large amplitude radial pulsation. The interaction of envelope pulsation with the stellar wind may increase the mass loss rate. The mechanism that drives the stellar wind and mass loss is not yet understood. It may be pulsations, expansion of the envelope, and radiation pressure on the dust grains result in increasing the mass loss rate. Further observations of type II OH/IR Miras which have large mass loss rate may provide clues to understand the mass loss process.

The idea that planetary nebulae are ejected for red-giant stars was first suggested by Shklovski. For the formation of a planetary nebula a very efficient mass loss process called superwind type of mass loss to distinguish it from the normal wind was introduced (Iben and Renzini 1983). In this picture low and intermediate mass stars ascent the AGB losing mass at a normal red-giant mass loss rate (Reimers mass loss rate) and when a critical luminosity is reached most of the residual H-rich envelope is ejected on a time scale very short compared with the previous AGB lifetime. Hydrodynamical models of the AGB stellar envelopes indicate that the superwind is triggered by the switch in pulsation from overtone to fundamental pulsation and it consists of a series of discrete ejections and the complete envelope removal takes place in about 1000 years (Iben and Renzini 1983) with mass loss rate ranging from 10^{-5} solar masses per year to 10^{-3} solar masses per year. AGB stars undergoing such mass loss rates on the verge of the termination of the AGB phase should be imbedded in a dusty and optically thick circumstellar envelopes. Such objects are very bright in the infrared and the optical counter part is completely obscured by the dust envelope. OH/IR stars, non-variable OH/IR stars, very dusty IR carbon stars and IRAS sources with far-IR colors similar to planetary nebulae and with no optical counter parts are the examples.

The onset of rapid mass loss phase on the AGB (super-wind regime) marks the beginning of a rapid decrease in the envelope mass of an AGB star. As the envelope mass decreases the star departs from the AGB at a rate that increases with decreasing envelope mass and the AGB phase of evolution is terminated and it marks the beginning of the post-AGB stage of evolution. The superwind mass loss ceases when the envelope mass falls below a critical value. The ejected matter keeps expanding and the remnant star continues its evolution towards higher temperatures with nearly constant luminosity and decreasing radius. When the temperature of the post-AGB stars reaches to about 30,000K the ejected matter becomes ionized and now assumes the characteristics of a planetary nebula. The post-AGB star continues to evolve to higher temperatures and moves closer and closer to the white dwarf cooling track and the nebula keeps expanding and eventually disperses into the interstellar medium. This simple picture described above depicts the evolution of low and intermediate mass stars from the AGB to PN stage. However in real life the picture is not that simple and the evolutionary time scales and stages are very sensitive to initial mass, mass loss rate during the AGB and post-AGB stage, chemical composition, rotation, binarity etc, and mass of the remaining envelope after the superwind phase or the termination of the AGB phase. Because the AGB and post-AGB evolution is sensitive to initial stellar parameters and the remnant envelope mass it is not easy to compare the theoretical predictions with observations.

5. Post-AGB stars

The difficulty in understanding the post-AGB evolution is that we have no idea of the mass of the envelope after the termination of the AGB phase by the superwind process. The evolution from the tip of the AGB to the young PN stage takes place in a few thousand years. During this short time the appearance of the central star plus the expanding circumstellar envelope changes dramatically. This protoplanetary phase is now being explored as a result of the IRAS. From the analysis of IRAS data several post-AGB stars have been detected (Parthasarathy and Pottasch 1986, 1989; Parthasarathy 1993; Kwok 1993; Hrivnak 1997; Reddy and Parthasarathy 1996). Most of these objects have far infrared colors similar to planetary nebulae. In the optical their spectral types range from K to B supergiants with many F-G supergiants, which is the temperature range expected as the low and intermediate mass stars evolve from the AGB to PN. These stars show supergiant like spectrum because around the C-O white dwarf like core there is only very little envelope mass which is very extended. Because of the very extended atmosphere the spectrum is similar to that of a supergiant. Parthasarathy and Pottasch (1986) suggested that the dust shells around the high latitude A and F supergiants and IRAS sources with far-IR colors similar to PN are the result of severe mass loss during their AGB stage of evolution and that these are low mass stars in post-AGB stage of evolution. The CO millimeter observations (Likkel et al. 1987) have revealed molecular envelopes with characteristics similar to that of evolved stars. They also show unusual 3 micron and 21 micron emission features. The chemical composition of the post-AGB stars also shows that these are evolved low mass stars which have experienced second and third dredge-up episodes (Parthasarathy et al. 1992; Reddy et al. 1997; Reddy et al. 1996).

An analysis of IRAS data shows that the following types are low mass stars in post-AGB stage of evolution: (i) high galactic latitude supergiants (many of them with dust shells), (ii) IRAS sources with far-infrared colors similar to planetary nebulae and with optical counter parts showing B to K supergiant like spectrum, (iii) RV Tauri stars, (iv) UV bright stars in globular clusters. Some or all of the following characteristics clearly indicate that these are low mass stars in post-AGB stage of evolution. The high galactic latitudes and or high velocities, low metallicities, cold detached circumstellar dust shells, molecular (CO) envelopes, H-alpha emission, small amplitude light and velocity variations, unusual emission features in the infrared attributable to carbon based dust, over abundance of carbon and s-process elements, in some cases extreme metal deficiency as a result of depletion of refractory elements in the fractionation process.

Recent work indicates that some of the high-latitude low gravity blue stars and supergiants may actually be low mass stars in post-AGB phase of evolution (McCausland et al. 1992; Parthasarathy 1993a,b). The post-AGB stars evolve from the tip of the AGB towards left in the H-R diagram with constant luminosity. When they reach a temperature of the order of

30,000K the shell surrounding the star gets ionized and it is turned into a planetary nebula. The duration of the transition phase (from the tip of the AGB to young PN stage) is short as is evident from the evolutionary changes observed in the hot post-AGB star Hen 1357 (SAO 244567).

6. Very young PN Hen1357 (SAO 244567)

Hen 1357 ((SAO 244567) is a high latitude star and was found to be an IRAS source with far-IR colors similar to PN (Parthasarathy and Pottasch 1989). Parthasarathy and Pottasch (1989) were the first to suggest that it is a hot post-AGB star. In 1950 Henize classified it as a B or A type star with H-alpha emission. In 1970 Kilkenny and Hill (1975) obtained the optical spectrum and classified it as a B3e star and also observed UBV colors which are similar to that of a B1 supergiant. The IUE UV spectrum obtained in July 1988 and April 1992 show nebular emission lines indicating the formation of a planetary nebula and a rapid evolution of the central star. The optical spectra obtained since 1990 show nebular lines and it is totally a planetary nebula spectrum. Comparison of the 1971 optical spectrum of Hen 1357 with the spectra obtained since 1990 show that it has turned into a PN within the last 20 years (Parthasarathy et al. 1993, 1995). The IUE UV spectra of Hen 1357 obtained during the last eight years show that the central star is rapidly evolving. It is found that the central star has faded by a factor of 3 in the UV since 1988. The terminal velocity of the stellar wind as revealed from the blue shifted CIV (1550Å) P-Cygni profile has decreased from -3500km/sec in 1988 to almost zero in 1994 (Parthasarathy et al. 1995; Feibelman 1995). The CIV 1550A profile has vanished by 1994. The B type supergiant spectrum of Hen 1357 in 1971 suggests that in 1971 its Teff was around 20,000K. The present nebular spectrum and IUE spectrum suggests that the Teff of the central star now is of the order of 50,000K. Thus in 20 years the Teff of Hen 1357 changed form 20000K to 50000K. The fading of the UV continuum and the termination of the stellar wind mass loss suggests that the nuclear fuel is almost extinct as a result of post-AGB mass loss and the central star is rapidly evolving into a DA white dwarf (Parthasarathy et al.1995). The HST wide field planetary camera observations of Hen 1357 have revealed a two seconds of arc nebula (Bobrowsky 1994).

The fading in the UV continuum of the central star indicates that it is occuring at much lower temperature than that is expected from the theoretical models. For the central star to evolve as rapidly as is observed in the case of Hen 1357 , a core mass of 0.8 or more solar mass is required according to the theoretical post-AGB evolutionary models. However the central star luminosity indicates a core mass of 0.6 solar mass for which according to the post-AGB evolutionary models the evolution is rather slow. Therefore the observed rapid evolution and fading of Hen 1357 are not in agreement with theoretical models of post-AGB evolution. Post-AGB mass loss may be the cause for this rapid evolution of Hen 1357. No other PN in this phase of evolution has previously been caught or identified and studied.

7. References

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