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Birth and early evolution of planetary nebulae

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Abstract. Birth and early evolution of planetary nebulae is described. The study of the young planetary nebula Hen 1357 (Stingray Nebula) with HST is discussed. The observed characteristics of few interesting PPNe and PNe are described. The presence of multiple arcs or rings, knots, jets, collimated and bipolar out flows and disks shows the complex nature of mass loss process during the AGB and post-AGB phases of evolution.

1. Introduction

All stars in the mass range 1 to 8 solar mass go through the Asymptotic Giant Branch (AGB) phase, then into planetary nebula (PN) phase and finally end their evolution as white dwarfs consisting of carbon and oxygen. Study of AGB stars, post-AGB stars, PNe and their circumstellar shells enable us to understand the processes that occur during the advanced stages of evolution of low and intermediate mass stars. Nucleosynthesis, mixing and mass-loss play a key role. Last three decades of multi-wavelength observational studies of AGB stars, post-AGB stars and PNe has enabled us to understand how most of the stars evolve after completion of central hydrogen and helium burning through the AGB phase and how they subsequently develope into PNe.

2. Mass loss on the AGB

Stars evolving along the AGB suffer from continuously increasing mass loss. Observations indicate mass loss rates of the order of 10^{-7} $M_\odot$ / year to 10^{-4} $M_\odot$ / year. The mass loss winds are most likely dust-driven and the pulsations and shock waves may further contribute to enhance the mass-loss rates. At some stage the AGB star in completely obscured by the dusty circumstellar envelope. AGB stars exhibit a large-scale surface convection which may lead to in homogeneities in the dust formation process and clumpy outflows. Finally the mass loss terminates the AGB phase of evolution when the envelope mass of the star is reduced to a few hundredth of solar mass. After the termination of the AGB phase the star evolves from the tip of the AGB towards the regime of central stars of planetary nebulae (Schönberner 1989). Even beyond the AGB the evolution depends on the preceding mass-loss history. Since mass loss determines the life-time on the AGB, it also determines not only the final mass but also the internal temperature density structure reached at the tip of the AGB and thus, the time scales

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for the post - AGB evolution and into white-dwarf (Blöcker 1995a,b).

PNe represent the short-lived evolutionary link between the tip of the AGB and the regime of the white dwarfs. There are very few complete AGB evolution calculations from the main-sequence through to the planetary nebula phase with mass loss. In recent years two such studies have been made by Vassiliadis and Wood (1993) and Blöcker (1995a,b). New evolutionary calculations from the main-sequence until the final white-dwarf stage have been published by Vassiliadis and Wood (1993, 1994) and Blöcker (1995a,b). The most important thing is the inclusion of mass loss which then results in a unique combination of initial (main-sequence) and final (white dwarf) mass.

3. Post-AGB

Mass loss determines the final evolution along the upper AGB and hence also the transition into the PN region. In the Vassiliadis and Wood models the post-AGB evolution starts at 5000K for low remnant masses and at 3500K for a remnant mass of 0.9 $M_\odot$. The transition times from the tip of the AGB into the PN regime behave quite differently in the models of Vassiliadis and Wood and Blöcker (Schönberner 1997). The coolest post-AGB stars are known to have about 5000 K effective temperature and kinematical ages of the youngest planetaries are only of the order of 1000 years. Infact from the analysis of IRAS data we have found several cool post-AGB stars with effective temperatures lower than 5000K and several young low excitation PN much younger than 1000 years (Parthasarathy 1993). Schönberner (1997) suggests that as long as there is no consistent theory available that describes mass loss on and in the vicinity of the AGB the models of Blöcker (1995b) are to be preferred.

The evolutionary time from the termination of the AGB phase to PN phase and also up to the turn-around point in the H-R diagram is given by the available fuel(i.e. the envelope mass during the post-AGB phase) divided by the hydrogen luminosity. Because the envelope mass decreases and the luminosity increases with remnant mass the crossing times are dependent on the remnant mass. For 0.94 $M_\odot$ post-AGB star the crossing time from 10000K to the turn-around point in the H-R diagram is about 50 years and for 0.6 $M_\odot$ post-AGB star it is about 4000 years and for a 0.55 $M_\odot$ post-AGB star it is 100,000 years.

The termination of the AGB phase as a result of severe mass loss marks the beginning of the post-AGB / proto-planetary nebula(PPN) phase. A PPN consists of a central post-AGB star evolving to the left on the H-R diagram, surrounded by a detached expanding circumstellar envelope of gas and dust. Observationally, the coolest PPN/post-AGB stars have spectral types of late G or early K supergaints (Parthasarathy and Pottasch 1986, Pottasch and Parthasarathy 1988, Parthasarathy 1993). photoionization occurs when the temperature of the central star reaches to 30,000 K, and we see the nebular emission lines in the optical spectrum and we regard this as the beginning of the PN stage. Therefore the effective temperatures of the post-AGB stars or the transition region objects and their spectral types range from 4000K to 30000K, or early K supergaint to O-B supergiants. They mimic the spectra of supergiants because they have extended atmospheres even though the mass in their envelopes (atmosphere around the core) is of the order of 0.02 - 0.03 $M_{\odot}$. The cool post-AGB supergaints to hot post-AGB supergiants forms an evolutionary sequence in the transition region (Parthasarathy 1993).

Most of the PPNe are compact or stellar in appearance. However recent high resolution imaging of PPNe with HST and with the ground based telescopes in the mid-infrared has revealed the bipolar, asymmetrical geometry and concentric rings in several PPNe. Resolving the images of PPNe can allow one to study the process that go into shaping the PN and to understand how asymmetry develops during the AGB and early post-AGB mass loss episodes. Mid-infrared imaging can allow one to see the geometry of the dust envelope directly. The mid-IR images reveal the geometry of the inner regions of the dust shells which samples the most recent phases of mass loss. Observations show evidence for axially symmetric superwinds.

4. Carbon-rich post-AGB stars

Red gaint stars are believed to evolve along the AGB through the M-MS-S -C sequence. Along this sequence the abundance of C12 increases by mixing of helium-burning products in the stellar surface. Thus the evolution along the AGB and third dredge-up transform an oxygen-rich AGB star into a carbon-rich AGB star with overabundances of s-process elements and C12. The hypothesis that carbon-rich AGB stars with high mass loss rates evolve into planetary nebulae (Zuckerman et al. 1976) is well supported by the result that approximately half of the mass loss from AGB stars in the solar neighbourhood results from carbon stars (Jura and Kleinmann 1989) and that half of all planetary nebulae in the solar neighbourhood are carbon-rich (Zuckerman and Aller 1986).

Planetary nebulae (PNe) reflect the evolutionary histories of the AGB stars that preceded them and carry the by-products of nuclear burning-enriched levels of helium, nitrogen and carbon. PNe allow to determine how the production of chemical elements depends on initial mass or metallicity and how the products are dredged up during the late stages of stellar evolution. Carbon abundances of post-AGB stars and PNe are of particular interest in this respect. The link between AGB stars and PNe is most directly seen from presence of the remnants of the AGB molecular envelopes and dust shells around several PNe and post-AGB stars.

The chemical composition analysis of post-AGB stars show that the post-AGB stars / PPNe with 21 micron emission are all carbon-rich and over-abundant in s-process elements. The CO and HCN millimetre wave observations and infrared spectra indicate that the dust shells around these stars are also carbon-rich. Recently, using mid-infrared spectra of several carbon-rich post-AGB stars with 21 micron emission Justtanont et al. (1996) found in addition to the standard UIR features attributed to PAH, new features at 7.9, 8.2, 10.6, 11.5, and 12.2 microns, which they attribute to PAH molecule chrysene. The UIR features were also observed in several young carbon-rich PNe and in PNe with [WC] central stars. All post-AGB stars with 21 micron emission are found to be carbon-rich and overabundant in carbon and s-process elements indicating that they have gone through the third dredge-up and carbon star phase on the AGB (Parthasarathy et al. 1992, Hrivnak 1995, Decin et al. 1998, Reddy et al. 1997, Zacs et al. 1996, Van Winckel 1997). Since these post-AGB stars and their dust shells are carbon-rich, as they evolve to higher temperatures they form carbon-rich PNe with carbon-rich central stars such as the PNe with [WC] central stars.

5. Imaging of PPNe and PNe

Multiwavelength spectroscopic and imaging studies of post-AGB stars, PPNe and young PNe detected from an analysis of IRAS data has enabled us to understand the birth and early evolution of PNe. Long term monitoring of post-AGB stars and PPNe is making it possible to study the stellar evolution in real time. Particularly the studies of Hen 1357 (Stingray nebula), AFGL 2688, Red-Rectangle, Helix Nebula etc reveal for the first time the phenomenon during the birth and early evolution of PNe.

5.1 Hen 1357 (Stringray Nebula = IRAS 17119-5926 = SAO244567)

Hen 1357 was discovered to be a young planetary nebula by Parthasarathy et al. (1993). It is a high galactic latitude object with far infrared colours (IRAS) similar to planetary nebulae (Parthasarathy and Pottasch 1989). In 1950 its spectrum was similar to that of a B or A type star with H-alpha emission (Henize 1976), but more recent observations by Parthasarathy et al. (1993) showed strong forbidden nebular emission lines consistent with a young planetary nebula.

The IUE ultraviolet spectra obtained during the last eight years show that the central star is rapidly evolving into a DA white dwarf (Parthasarathy et al. 1995). The IUE UV spectra of the central star show that it has faded by a factor of 3 within the last eight years. This is consistent with the fact that when hydrogen burning cannot be sustained any longer because the envelope mass becomes too small, the surface luminosity must drop very fast by at least one order of magnitude until the gravo-thermal contribution is reached.

In 1971 the optical spectrum of Hen 1357 was similar to that of a B1 supergiant. However in 1990 the optical spectrum of Hen 1357 is similar to that of a planetary nebula. And in fact the HST high resolution images have revealed the presence of a planetary nebula with a diameter of 1.6 seconds of arc and a companion star 0.3 seconds of arc from the central star (Bobrowsky et al. 1998). These results confirm the earlier conclusion of Parthasarathy et al. (1995) that Hen 1357 has turned into a PN within the last 20 years.

The HST high resolution Wide Field Planetary Camera (WFPC2) images of Hen 1357 in nebular emission lines and continuum (Bobrowsky et al. 1998) have enabled us to study the birth and early evolution of a planetary nebula. The final expulsion of gas by star as it forms a planetary nebula is one of the most poorly understood stages of stellar evolution. Such nebulae form extremely rapidly (about 100 years for the ionization) and so the formation process is difficult to catch and observe. The HST observations and analysis of Stringray Nebula (Hen 1357) were reported by Bobrowsky et al. (1998) which has become an ionized planetary nebula within the past 20 years (Parthasarathy et al. 1993, 1995). We find that the collimated outflows are already evident, and we have identified the nebular structure that focuses the outflows. We have also found a companion star indicating that it is playing an important role in shaping planetary nebulae and changing the direction of successive outflows.

We find the parameters of the nebula and central star of the Stringray nebula (Hen 1357) to be : electron density = 10^4 cm^{-3}, electron temperature = 10000K, distance = 5.6 kpc, radius of the nebula = 0.025 pc, nebular mass = 0.015 $M_\odot$, core mass 0.6 $M_\odot$, central star luminosity = 3000 $L_\odot$.

The B1 supergiant type spectrum and the UBV photometry in 1970 suggests that the effective temperature of Hen 1357 in 1970 was of the order of 20000K (Parthasarathy et al. 1995). The present effective temperature of the central star is estimated to be more than 50000K (Parthasarthy et al. 1995). The fading of the UV flux (Parthasarathy et al. 1995) of Hen 1357 and the increase in temperature at this stage imply a drop in the total luminosity of the central star. This places the central star of the Stringray nebula at the knee of the H-R diagram, just before the star evolves towards lower temperatures and lower luminosities. However, these observations reveal that the post-AGB mass loss is an important aspect and the inadequacy in the current theoretical understanding of how these stars evolve. For the central star to evolve as rapidly as observed in the case of Hen 1357 (Stringray Nebula) the core mass of the central star to be of the order 0.8 $M_\odot$ or more is needed. However the luminosity of the central star indicates a core of 0.6 $M_\odot$ or less, for which the evolution is expected to be much slower than observed. May be post-AGB mass loss and complete loss of the envelope and hence hydrogen burning has not sustained any longer because the envelope mass became too small, may be the cause of the unexpectedly rapid evolution. This may be the cause for the differences between observations and theory. The observations clearly show that the central star has become a planetary nebula only within the past 20 years and it is rapidly evolving to become a DA white dwarf (Parthasarathy et al. 1995).

Earlier one was able to image and study the ionized nebulae with low resolution imaging only. Now with the high resolution imaging techniques in the UV, optical, mid infrared, millimetre and radio wavelengths it has become possible to study the geometry and structure of the circumstellar envelopes from the AGB stage to young and advanced PNe stages. One can now trace the history of the AGB to post-AGB mass loss episodes. Ground based mid-IR (8 to 20 micron) imaging of the thermal dust emission from PPNe and WFPC2 HST imaging of the central star light scattered by the PPNe dust shell reveal the morphology of the dust shells and sample mass loss phases which ended the stars life on the AGB. PPNe imaged at mid-IR wavelengths are resolved and appear axially symmetric bipolar. The axially symmetric structures were created by a superwind mass loss phase which ended the star's life on the AGB.

5.2 CRL 2688

With HST WFPC2 several young PNe and PPNe (Sahai et al. 1998) have recently been imaged with unprecedented high angular resolution and dynamic range. Young PNe are characterised by multipolar bubbles distributed roughly point-symmetrically around the central star. In some post-AGB stars bipolar or collimated radial structures are seen indicating the presence of jets, whereas in others bright structures near the minor axes indicate the presence of disks or torii. These results indicate that the asymmetries are produced during the AGB mass loss phase. The existence of arcs suggests that periodic mass loss enhancement is a common phenomenon in the AGB phase. For example the dust envelope of CRL 2688 (Sahai et al. 1998) consists of many arclets or thin dust shells. The thickness of the shell is approximately 10^{16} cm. Narrow double beams of the scattering light were also seen. There are about 20 concentric shells with a roughly uniform spacing of 0.5 seconds of arc or 0.003 pc. For a typical outflow velocity of 20 km/sec this implies a period 200 years between the rings. It is likely that CRL 2688 has gone through several mass loss episodes with an interval of the order of 200 years.

We need to understand the origin of these multiple shells and rings in CRL 2688 and other PPNe. The presence of similar concentric rings and shells in few other post-AGB stars / PPNe indicates that it is related to the birth and early evolutionary stages of planetary nebulae. It is likely that the gas-dust flow is intrinsically unstable and also the mass loss may terminate periodically. Also an instability of radiation driven or dust driven gas-dust flow may also result in such multiple shells and rings. Another possibility is that these objects like CRL 2688, He3-1475, IRAS 17150-3224, IRAS 17441-2411, Roberts 22, Red Rectangle, M1-92, MyCn 18 and KjPn8 which are very young PPNe and post-AGB stars have a close binary companion embedded in their dusty disks. The presence of a close binary companion may play a significant role in shaping the nebula and the disk during the AGB and post-AGB mass loss phases.

5.3 He3-1475

He3-1475 was found to be an IRAS source by Parthasarathy and Pottasch (1989) with far-IR colours similar to PN. They concluded that it is a hot post-AGB star evolving rapidly into a young PN. Recent multi-wavelength observations show that it is surrounded by an expanding torus of molecular material (seen in CO, OH and in scattered light) and a small dense ionized PN seen by the VLA. The most spectacular feature of He3-1475 is its bipolar optical jets which emerge perpendicular to the torus and which terminate as a series of point-symmetric knots. The flow velocities are of the order of 400-800 km/sec and the optical line emission is apparently due to shock excitation. High resolution images taken with HST WFPC2 show large scale hydrodynamical flows being collimated into narrow jets. This indicates that the narrow jets need not originate in small scale structures, such as accretion disks. They can also originate in the bipolar outflows of post-AGB stars. MyCn 18 is in some respects similar to Hen 1475. MyCn 18 is a young PN. HST observations show irregular knots of emission outside the main nebular structure. The knots are moving with velocities of more than 500 km/sec away from the central star making them among highest velocity outflow ever observed from a PN. A bipolar rotating episodic jet mechanism is favoured for their origin. Similar collimated outflows or jets are also observed in another young PN Kjpn 8.

5.4 Helix Nebula

Ground-based images taken at mid-IR wavelengths often show axially symmetry in proto-planetary nebulae (Meixner et al. 1998). However in many young PNe pronounced inhomogeneity has been observed. They appear to be clumped on the smallest size scales observed. An extreme form of clumpiness has been observed in the Helix nebula. From HST high resolution imaging O'Dell and Handron (1996) find about 3500 cometary knots in the Helix Nebula (NGC (7293). There cometary knots seem to be stable and their life time may exceed that of the PN stage. The mass of each cometary knot is estimated to be of the order of 10^{-5} $M_{\odot}$. We do not

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yet understand what will be the fate of these cometary knots, if they survive. If they are gravitationally bound, they will eventually collapse into solid bodies, leaving behind a cooling white dwarf surrounded by thousands of planets. Many post-AGB stars are having stable dusty disks and dust shells with significant amount of dust mass. It is likely that planets can form from these dust disks and shells around the post-AGB stars.

Rayleigh-Taylor instabilities seem to be the most likely source, arising from either the earliest stages of the planetary nebula development at the ionization boundary between the ionized and neutral components. The origin of these cometary knots in Helix nebula is not clear. Such knots may exit in other PNe also. We need to wait for the high resolution images of large sample of PNe. The origin of these knots may be the results of large-scale surface convection during the AGB phase at which time mass ejection in the form of giant bubbles of gas may have occurred.

5.5 The Red Rectangle

The X-shaped reflection nebula (Cohen et al. 1975) hosts a central binary with a luminous post-AGB star (HD 44179) of T_{eff} of about 7500K. The central post-AGB star of red rectangle is an eccentric binary system (Waelkens et al. 1996). It belongs to the small class of extremely metal deficient binary post-AGB stars. High resolution opitcal and near-IR imaging revealed the presence of an optically thick circum-binary disk (Roddier et al. 1995, Osterbart et al. 1997, Bond et al. 1997). The disk appears to be quite stable and long lived (Jura et al. 1995). ISO-SWS spectrum of red rectangle shows PAH bands and also at longer wavelengths emission from crystalline olivines and pyroxenes are detected (Waters et al. 1998). The nebula and the central star of red rectangle are carbon-rich. The oxygen-rich dust seem to originate from the disk. It is likely that the condition in the dusty disk in the red rectangle may eventually lead to planet formation (Water et al. 1998a, Jura and Turner 1998). Recently Jura and Turner (1998) discovered a cool and large structure in the dust cloud of red rectangle. The presence of oxygen - rich dust in the carbon-rich dusty nebula indicates that the transition from oxygen-rich phase to carbon-rich phase has taken place only recently.

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