

The Evolution of Planetary Nebulae

The connection between stars and the gaseous envelopes we now call planetary nebulae was not evident to observers of the past. William Herschel's 1784 insight was the first step on the road to a fuller understanding. Today, astronomers are concerned with modeling the minutiae of planetaries, and although we have a far greater understanding than our historical counterparts, there are still many problems to be overcome in our quest for a final agreement between observation and theory.

The Lives of the Stars

Planetary nebulae are the end product of particular stars. That is, they are the end result of stars with a particular range of masses, as it is mass that determines what sort of life and what sort of endpoint such stars become.

Stars are born out of huge clouds of gas and dust that exist in the spaces between the stars within a galaxy such as the Milky Way. This interstellar medium (ISM), as it is known, consists of primordial hydrogen and helium with an enrichment of heavier elements from the deaths of previous generations of stars. The ISM contains small amounts of almost every element on the periodic table, but the elements of smaller atomic mass predominate; elements up to iron are common in space even though their abundances are very small in comparison with that of hydrogen and helium.

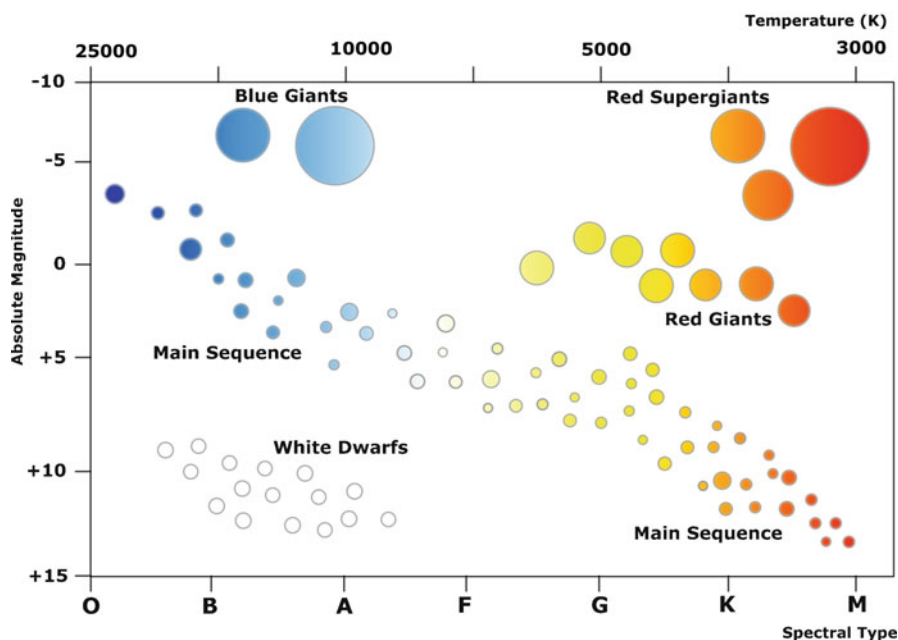
Stars are born from the ISM when gravity begins to pull the material together after an initial overpressure from a density wave or supernova, compresses this otherwise inert material. Once there is a local density within the ISM, gravity begins to bring the material together in greater amounts until the dense cloud begins to fragment into individual units – proto-stars within proto-clusters. The initial mass of each proto-star to some degree determines the future evolutionary pathway of the star, although mass loss can still take place at this and later stages in the life of a star.

Once the temperature at the core of a proto-star becomes sufficient to fuse hydrogen into helium in the interior, the resultant flood of radiation away from the core and surface stop further aggregation of material, and within a few million

years a star will settle into a regular and steady luminosity. This luminosity will be dependent on its mass; for stars between one and eight times the mass of our Sun, the radiation trickling out of them will sustain such luminosities for a few billion years.

In this rather simplified scenario, stars will convert hydrogen into helium for a significant fraction of their lives. Stars that accomplish this are known as main sequence stars and can be found situated on the S-shaped curve of the accompanying diagram. Their position is dependent on their mass. A star of one solar mass will release the bulk of its energy in the visible part of the spectrum and is predominantly yellow in color. A more massive star will convert hydrogen to helium at an increased rate as the internal pressures squeeze more materials together in the core, which results in a larger rate of nuclear reactions. Such stars will be yellow-white or white while larger ones will be blue in color and exhibit themselves at the top left of the diagram. Those stars that are dim and red will occupy the opposite part of the diagram at the bottom right. The diagram gives us a quick view of the stellar temperatures, colors, luminosity and an indication of mass while the star remains on the main sequence.

Louise Mayall and Annie Jump Canon first classified the spectral sequence within the H-R diagram in the early twentieth century at Harvard college observatory. Canon took over the early work by Mayall and turned a vague classification into a powerful detecting device by tying the colors, temperatures and chemical signatures of the stellar spectra into a tool that went from high to low on the temperature scale, which then matched the color of the star and its luminosity on the main sequence. Her classifications are shown here in the following table.



Hertzsprung Russell diagram.

Harvard spectral sequence

Spectral type	Temperature (K)	Colour	Characteristics
O	40,000	Blue	Ionized helium and few metals, weak hydrogen lines
B	25,000	Blue-white	Neutral helium stronger hydrogen lines
A	12,000	White	Hydrogen lines dominant, ionized metals appearing
F	8,000	Yellow-white	Hydrogen weakening, neutral and ionized metals
G	6,000	Yellow	Ionized calcium prominent, neutral and ionized metals
K	4,000	Orange	Neutral metals prominent molecular lines appearing
M	3,000	Orange-red	Titanium oxide prevalent, molecules dominant and neutral metals
R	2,500	Red	CH and CN dominant and neutral metal lines
N	2,500	Red	CH and CN dominant and neutral metal lines
S	2,500	Red	Zirconium oxide prevalent, neutral metal lines common

This sequencing enabled astronomers to discover the life cycles of stars and account for their various positions on the H-R diagram. As their knowledge increased, they were able to explain the changes stars undergo during their latter stages to become planetary nebula. The sequence and the H-R diagram together are wonderful implements that give the trained mind give a quick representation of expectations over the lifetime of a star.

Stages in the Life Cycle of a Sun-like Star

It is the relatively small- to medium-sized stars that will undergo evolution to the planetary nebula stage. The diagram below reveals the basics of the changes the star will suffer and the predicted track across the diagram to an end point. If one starts with a Sun-like star with a temperature of 6,000 K and a yellow color, such a star will convert hydrogen into helium in its interior for about 8–10 billion years. Known as the proton-proton chain, wherein four hydrogen nuclei are converted into a helium nucleus, this process is dependent on core temperature. Above a temperature of 17.5 million K the CNO process, or carbon, nitrogen, oxygen process, dominates, where these elements become the catalysts to convert four hydrogen nuclei into a helium nucleus. The end product is the same, though the energies in the process are subtly different. This conversion from hydrogen to helium is a very stable process despite its very high temperatures, and the energy flow maintains the star's radiative output for a very long time.

Once there is sufficient helium build up in the core to significantly interfere with the hydrogen reactions, the core shuts down and begins to contract. However, there is a lot of latent energy in the overlying layers from radiation attempting to escape the outer envelope. As a consequence of this radiation pressure, the star will begin to expand as gravity works primarily upon the greater mass of the core and only has a relatively weak effect on the outer layers. At this point the core contracts and the outer layers expand. To an external observer the star now star begins to cool as it expands and moves toward the right of the diagram, off the main sequence.

As it does this, the spectral signature of the star changes as it cools to an orange K type sub-giant. The star then utilizes the energy of hydrogen–helium conversion, which now takes place in a shell around the inert hydrogen core rather than throughout the core, as in its previous incarnation. Over time the star will continue to expand and cool until it becomes a red giant. It is now large, luminous and has an extensive solar wind, which is driving the material of the outermost layers off the star. This expulsion of material is important in the development of a planetary nebula. Under such forces, a star can lose as much as 1/100,000th of a solar mass per year. One can imagine that this is not a stage that can last too long.

Eventually, gravity compresses the helium core until sufficient pressures and temperatures build up inside to fuse helium to carbon in a process where three helium nuclei make one nuclei of carbon – the triple alpha process. Once a new source of energy has been established, the star attempts to move back toward the main sequence, as can be seen in the above diagram. However, there is insufficient helium fuel to power the star, and as this fuel becomes exhausted, the outer layers expand again with latent energy from the radiation release and are eventually lost to space with an increase in the power of the stellar wind at this stage. Once the luminous outer envelope of the star is lost, the naked core is all that is left, a small, hot remnant with a fraction of the luminosity of the whole star, and the object dims appreciably and makes its way rapidly down to the bottom left on the diagram to end its days as a white dwarf.

This simplistic view is the broad facet of what astronomers have gathered over the last century. The detail of what happens during the planetary nebulae stage is all-important to our understanding of the stellar life cycle.

The Asymptotic Giant Branch

The most important phase in a star's life that leads to the expulsion of material forming part of a planetary nebula is that of its course as an asymptotic giant. In the H-R diagram above, this course is represented by a horizontal line between the giants and super-giants leading to the left of the diagram. The kinds of pulsations the star will undergo, the chemical enrichment and core burning stages at this phase are dependent on the initial mass of the star.

It is difficult to accurately define exactly what a low, medium and high mass star is. Astronomers use generalized terms that cover a variety of options in mass to determine which category a particular star will fit into. Generally speaking, a low mass star ranges from 45% of the mass of the Sun to two times this mass; a medium mass star will be measured as one between two and five solar masses, while a high mass star can be anything above this level, culminating in masses that can be measured between 5 and 40 times the mass of the Sun. Planetary nebulae are known to derive from relatively low mass stars, so some confusion may result among the usage of such terms, especially when one considers that recent developments in planetary nebula research have discovered nebulae with a total mass (gas and central star) of around eight times the mass of our Sun.

From our perspective, the mass of the progenitor star on the AGB is important in that this initial mass will define the chemical makeup of the central stars and indicate the constituents of the surrounding gaseous shrouds. Low mass stars

(1 solar mass) on the AGB will produce carbon-rich end products, including the central star. Intermediate mass stars (2–3 solar masses) will produce cores rich in carbon and oxygen, while higher mass stars (3–6 solar masses) will have nitrogen- and neon-rich cores. This mass function also has implications for the evolution of the outer envelopes of the stars and their variability, stellar wind and thermal pulsations.

To the external observer, the star still follows the Harvard classification system, as our observations cannot penetrate the opaque core where all this interesting nuclear physics is occurring. Therefore, most AGB stars are classified as M, R, N or S, designations that have mostly been replaced by a collective term C, or “carbon stars.” Such stars have an abundance of carbon or oxygen in their photospheres, as there is an exchange of material between the core and the photospheres in such stars due to the nature of their convective cores. Some AGB stars have photospheres that are heavily obscured by carbon dust, which indicates the nature of their cores. Others have high incidences of oxygen and the spectral signatures of silicates. Due to the obscuring nature of such dust, much current research is done in the infrared, and there is excellent correlation between infrared and optical spectroscopy on AGB stars. Any one of these spectral signatures is of interest to astronomers researching the production and evolution of planetary nebulae.

Stars that are only 45% of the Sun’s mass do not become AGB stars; rather they cross the horizontal branch of the H-R diagram and become C-O white dwarfs, which then gradually fade away after their hydrogen envelopes have been lost during the planetary nebula phase. The upper limit for low mass stars is somewhere in the region of 2.2 solar masses, according to recent research. Low and intermediate mass stars become AGB stars once they have exhausted helium burning and develop an electron degenerate C-O core. During this phase, the star burns both residual hydrogen and residual helium in two thin shells surrounding the degenerate core. During the early phases of the AGB the hydrogen shell is extinguished as a result of expansion of the star, and helium burning provides the luminosity, but hydrogen in the outer parts of the core re-ignites at later stages and contributes to the thermal pulsations of the star, thus accelerating the mass loss. As helium also becomes dense enough to undergo further nuclear reactions in the core, pulsations are set up that cause the star almost literally to oscillate and lead to greater mass loss during this stage, which is known as the Thermal Pulsing Asymptotic Giant branch, or TP-AGB.

This pulsation is of central importance in the production of planetary nebulae. Many photographs from ground and space observatories reveal materials external to the main body of the planetary nebula, which derive from former mass loss due to pulsation. Pulsating AGB stars become long-period variables like α Ceti or Mira and recent studies of Mira reveal a long tail of lost materials released by its pulsations as it moves across the heavens. Studies of M57, the Ring Nebula in Lyra, also show much material outside that of the main shell released in the distant past when the progenitor was an AGB star. It seems this pulsation on the AGB phase is a common feature of mass loss, and such losses have been noted to be as much as 10^{-5} of a solar mass per year, indicating that AGB stars can lose substantial mass during this phase. Indeed, considering the timescale for the nuclear power production rates in the core, such mass loss can exceed the core lifetime by two or three orders of magnitude, which determines the lifetime of the AGB phase as that controlled by the mass loss rather than from core nuclear burning. It is easy to see therefore

that even high mass stars may lose substantial amounts of material and slim down to produce cores that are below the Chandrasekhar limit (1.4 solar masses), thus ensuring that such stars can also produce planetary nebulae.

The mechanisms of such mass loss have been debated for some time. It seems reasonable to conclude that there are probably three main models with one or more of the mechanisms working together. The main mass loss at the AGB phase comes from thermal pulsation, stellar winds and radiation pressure. The radiation pressure drives both gas and silicate or carbonate dust away from the star, but measured speeds of around 50 km/s indicate that this process also carries gas away with the grains as the expected speeds should be much higher than this. Stellar winds will carry away materials from the photosphere at an increasing rate, and the thermal pulsations due to the energizing of the hydrogen and helium burning shells will add to the mass loss as large portions of the photosphere expand and contract, resulting in ejection speeds that exceed the local escape velocity.

The AGB phase is possibly the most important aspect of the production of planetary nebulae. This phase typically lasts about a million years and, due to mass loss, can ensure that even some high mass stars will produce cores that will become white dwarfs, the central stars of planetary nebulae. Typically the termination of the AGB phase occurs when the hydrogen envelope is depleted by mass loss and the star then begins to evolve toward the blue side of the H-R diagram. At this stage the star is on its way to produce a planetary nebula. The ejection of materials and the buildup of dust in the circumstellar envelopes of AGB stars ensure that these materials will become important parts of the gaseous shrouds we recognize.

Before we discuss the production of the nebula, let us examine the early phases of this phenomenon in the light of recent research.

Proto-Planetary Nebulae and Dust

Once the loss of the majority of the hydrogen envelope has occurred, the star will move to the left- or blue-ward side of the H-R diagram, and its temperature will increase. Eventually the stellar remainder will become hot enough, until at about 25,000–30,000 K the ultraviolet output from the star will ionize the surrounding hydrogen shed during the AGB phase. At this point, the body becomes a planetary nebula, but this scenario omits a crucial stage in the story.

Once the star has shed the majority of its hydrogen shell, the remnant will continue to get hotter. As it does so, the previously shed materials begin to radiate in the infrared and a peak output in its spectra will be that of carbon monoxide (CO) emission from the circumstellar shell. In the visible spectrum, the Harvard class becomes F or G and its luminosity indicates it to be a very luminous giant. At this point most of the envelope is neutral, with no line emission to indicate what is happening to the underlying star; indeed the star may be obscured by carbon and silicate dust that is condensing out or has condensed out during the AGB phase.

The composition of this dust component is also partly dependent on core nuclear burning and thus initial stellar mass, as the resultant elemental abundance from core burning in relatively low mass AGB stars is carbon, while the products from core burning in intermediate to high mass stars will contribute oxygen, nitrogen and silicates to the circumstellar shell. These carbon and silicate grains are the major dust component of proto-planetary nebulae (PPN).

In some sources, spectroscopy reveals CH, OH, H₂O, CN, HCN, SiO, C₂H₂ (acetylene) and Fe₃O₄ (magnetite) in addition to nano-diamonds and fullerenes (C₆₀) to be present in large measure, while polycyclic aromatic hydrocarbons (PAHs) also provide a large spectral spike, all of which are exciting molecules for those interested in the chemistry of life. Even in death, stars becoming planetary nebulae contribute pre-biotic materials to the interstellar medium and the next generation of stars.

Naturally, as this phase is very short in the star's lifetime, such PPN are going to be very rare as optical objects but may be numerous as infrared objects. Studies in the infrared using IRAS (Infrared Astronomy Satellite) and ISO (Infrared Space Observatory) coupled to radio studies of thermal CO emission have shown about 100 candidates; NGC 7027 in Cygnus is one of the most studied candidates, as it is bright and relatively close enough to reveal detail (and indeed is visible as an object of study within this book). Other examples are the 'frosty Leo' nebula IRAS 09371 + 1212 (also visible to amateurs and included in this book) and the fabulous 'red rectangle' HD 44179 in Monoceros, which is visible as a starry point to most observers as it has an integrated magnitude of 9.2 (and is also included here).

Due to the combination of circumstellar dust and peak radiative output in the infrared, most PPN are relatively faint. It is possible, though, that the orientation of the nebulae may play a part in its visibility, as a 'pole on' nebulae will appear brighter as the circumstellar dust shells will primarily be lost in an equatorial disk initially and the central star may peep through the thinner polar clouds, resulting in the PPN looking more star-like than those visible as mere infrared objects. The dispersal of these dust shells and the emerging central stars with their high temperatures and ionization potential indicate the PPN is becoming a full-fledged planetary nebula. The dispersal of such shells indicate the presence of strong stellar winds, and it is to these winds and their dynamics to which we now turn.

Interactive Winds

During the AGB stage, the star is losing up to 10^{-5} solar masses per year in the form of a vast stellar wind. This high rate of mass loss explains why the AGB phase is terminated by the loss of the hydrogen shell rather than helium depletion in the core; the great mass loss leads to less gravitational pressure, and thus the core is not able to sustain high pressures and temperatures. This loss, exacerbated by thermal pulsing, contributes to the production of an expanding circumstellar shell in the PPN phase. However, a planetary nebula is formed when the hot and fast-moving winds from the uncovered core begin to compress and overtake these lost shells.

It was thought for many years that the thermal pulsations themselves were responsible for planetary nebula formation. However, initial investigations in the 1970s soon showed that the wind velocities in the expansion of stellar winds in AGB stars and those of the winds from hot central stars were significantly different, resulting in the astronomer Sun Kwok proposing the version now favored by most working in the field – the interacting winds model.

The expansion velocities of the stellar wind and thermal pulsation mass loss may be between 50 and 100 km/s; this gives the impression of a gently moving outwardly expanding mass of diffuse gas. However, the velocities of the hot winds that are given off by the central star are in the region of 1,000–1,500 km/s, much faster than the gentle winds described formerly. This fast, expanding super-wind

then hits the slowly expanding outer gases and creates a snow plough effect in that it collects this material and compresses it into the intricate structures we see in the shells of many planetary nebulae today. At the same time, the naked core of the central star is giving off vast amounts of UV radiation, which cause the gases to become ionized and then fluoresce, giving out the emission lines in the optical that are noticed by astronomers. Typical lines are H α , OIII, NII and SII, which are visible as bright lines against a dark backdrop in an optical spectrometer.

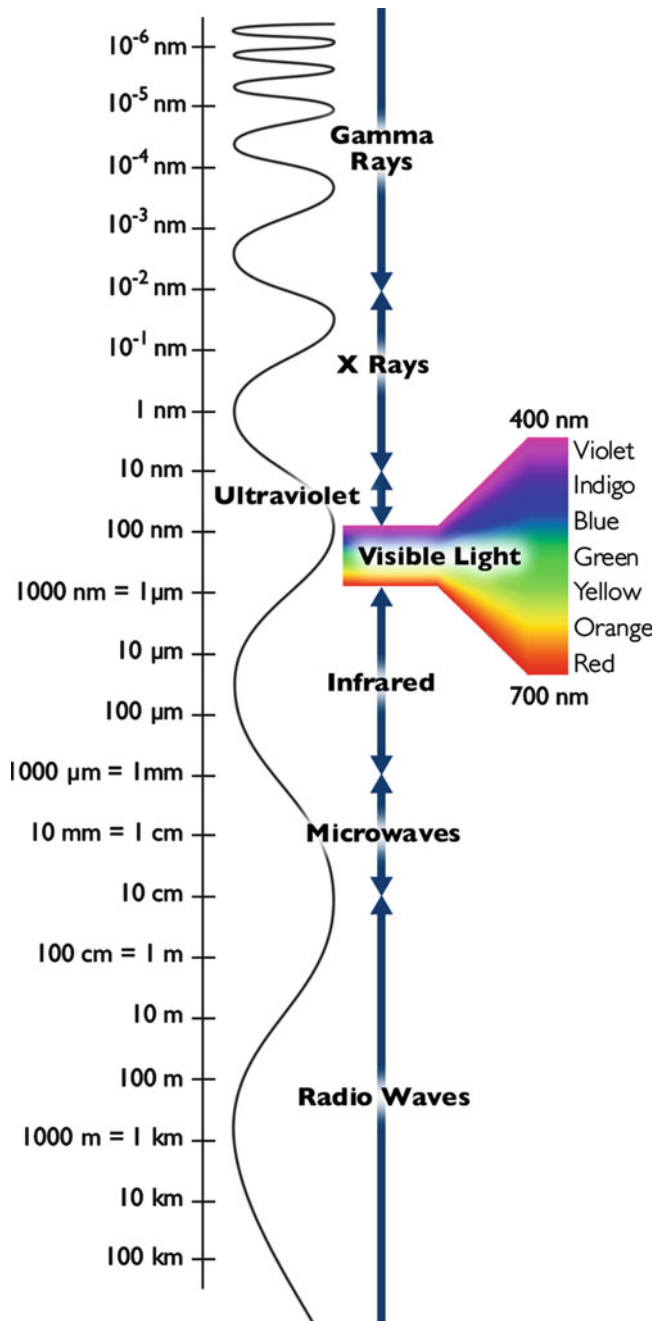
As the hot wind catches up with the materials released during the slow stellar winds and thermal expansion gases of the AGB stage, it causes the material to bunch up into a dense shell. Evidence of such interactions should come through deep sky observations of planetary nebulae in which a halo of material at great distance from the star would be visible as a slowly expanding shell, whereas within the interior of the planetary and at the densest parts of the nebulae, a high velocity wind should be measured. This is precisely what was found in surveys after this proposal; planetary nebulae are surrounded by large, amorphous, slowly expanding envelopes of material from the AGB phase while their densest parts and those closest to the central stars are dominated by fast-moving winds and ultraviolet light from the core. The various shell structures are explained by the interaction of the slowly moving AGB wind and the fast wind from the central star.

One of the predictions of this model was the presence of X-ray emission in planetary nebulae. When an object is moving faster than sound in a medium, a shock wave is generated, which in the case of planetary nebulae would be a shock wave occurring when the fast wind hits the slowly moving material. In the late 1990s this prediction was confirmed by both ROSAT and CHANDRA X-ray observatories, which found X-ray emission from the shocked region where the slow and fast winds collided.

The interaction of these winds and the inhomogeneous densities among the materials in the expanded layers are therefore responsible for the plethora of different shapes, densities and interior structures of planetary nebulae that render them such beautiful objects of study for amateur and professional alike. The nebulous shells that we so admire are an ever-changing spectacle, albeit on large timescales, that illustrate the intricate interface of winds from the star.

Emissions from Planetary Nebulae

The beautiful shells that thrill observers are responsible for the main emission spectra from the object. As planetary nebulae are primarily hot gas, their spectral characteristics are epitomized by bright lines against a dark background with no continuum, with the lines of OIII, H α , NII, NeIV and SII strongly represented in typical examples. In early surveys it was difficult to differentiate between emission nebulae and planetary nebulae, leading to confusion and misclassification of small but ordinary HII regions as planetary nebulae. A study of the Perek-Kohoutek catalogue by Aker et al. in 1987 re-classified 262 objects, almost a quarter of the catalogue as non planetary nebulae! This emphasizes the difficulties of classifying planetaries, although modern techniques have considerably refined the process. The Strasbourg ESO Macquarie study has added over 1,000 more planetary nebulae to the existing numbers of known objects of this type.



The electromagnetic spectrum courtesy of Faulkes telescope.

These errors in identification are due to the fact that emission nebulae and planetary nebulae have many lines in common. The main differentiating characteristic in planetary nebulae is the very low density of the gases involved. This low density leads to electron transitions within the atoms of the rarefied gas known as “forbidden lines,” of which the OIII, NII and SII lines are typical examples. Hydrogen lines present are due to electron recombination as the high temperatures in the gases do not allow neutral hydrogen to remain that way for very long, and the protons marry up with free electrons in what are termed “free-bound” transitions. There are also collisionally excited lines where a free electron may pass close by to an element that has retained most of its electrons but may cause an excitation by transferring energy to the element, resulting in the excited element giving off a photon.

Within planetary nebulae, forbidden lines, free-bound transitions and collisional excitation all work side by side to present a nebula that is visible across the electromagnetic spectrum from X-rays to radio. Untangling the atomic origins of this web of light has been one of the great success stories of twentieth-century science.

It is these narrow emissions that give planetary nebulae their distinct colors visible to the observer. OIII is strongly centered on the green part of the spectrum at 500 nm (the ‘nebulium’ of William Huggins), while OII is centered in the blue part of the spectrum at 372 nm. Observers often refer to the observable color as green or blue, though other distinct colors are seen, such as red, in bright planetary nebulae such as M57. These narrowband lines can be used to determine the existence of faint, diffuse or almost invisible planetary nebulae by the observer, by means of using specialist filters at the eyepiece. We shall refer to this technique later.

The gases of the planetary nebulae are at temperatures of 10,000 K or more and are mostly in an excited or ionized state. Where does the energy to heat the nebula come from?

Central Stars

Inside all planetary nebulae is the remnant core of the original star. This core, now shining blue-white and relatively dim in comparison to the expanding envelope, is responsible for the energy heating the gas. Once the AGB phase is ended, there may be a small remnant of hydrogen gas still surrounding the core. This gas is further depleted by a steady stellar wind, but not to the same extent as the initial huge mass loss during the AGB. Many central stars of planetary nebulae have been studied and have been shown to have the spectral characteristics of hydrogen present, indicating that our general understanding of this stage in a star’s life is fairly well understood. In some nebulae the central stars are burning helium, indicating that there may be a number of final thermal pulses that eject the hydrogen envelope. This late burning gives rise to the radiation responsible for the heating of the planetary shell.

Once this hydrogen or helium is exhausted, all that is left is a degenerate C-O core. At this stage, the core has settled down to a life where it no longer shines by nuclear fusion; rather it is now feebly radiating away by conduction and is now located astrophysically in the bottom left side of the H-R diagram. It loses luminos-

ity and temperature and is now a white dwarf. This remnant continues to radiate UV light that comes from the thermal energy released during gravitational contraction, adding to the ionization and excitation of the nebula, before the dwarf rapidly (astronomically speaking) cools.

White dwarfs are fantastic creatures. They are the compressed remnants of the cores of AGB stars and are primarily composed of carbon, the end result of helium nucleosynthesis. However, as most of the mass of a star is to be found at the core, the white dwarf becomes extremely dense as gravity crushes it, and the radiation pressure from nuclear burning no longer holds the star up. Eventually the atoms are squeezed together until they have very little room. The electrons within the atom take up positions in or close to their ground states, and as an atom is mostly empty space, the starry remnant can therefore become very small, just a few 1000 km in comparison to the millions of kilometers of the former giant. A star the size of the Sun, one million km in diameter, will have a diameter as small as Earth's, at 10,000 km.

The squeezed atoms are then subject to electron pressure, where they continue to be confined to the ground state of the atom, and they consequently begin to move at very high speeds in these orbits, holding off further collapse. This state is known as electron degeneracy, a condition that was first theoretically explored by the physicist Wolfgang Pauli in 1925. Under these circumstances, the star is extremely dense; a cubic centimeter of such material – the same size as a cube of sugar – can weigh many tons. The materials within the star eventually take up station where they are equidistant from each other to produce a crystalline lattice. In such a condition, a white dwarf consisting of carbon will become a very large and pure diamond!

Astronomers classify white dwarfs by the elemental abundances revealed through the spectroscopy. All white dwarfs have the appellation (D), indicating a degenerate star with the letters DA indicating the presence of hydrogen, DB indicating helium, DZ for metallic lines such as manganese or iron and DQ for stars with carbon or molecular carbon in their spectral lines. In this classification, one can have a mixture of letters such as DAZ, which acknowledges secondary features of importance in the spectra. However, considering that the great majority of white dwarfs arise from AGB stars, the remnants of their hydrogen envelopes are discernable and almost 80% of white dwarfs stars are DA types.

Slowly the white dwarf cools until it no longer shines, becoming a black, cold, dense remnant of its former glory. However, such end products are not our concern here, and we should revisit what happens during the planetary nebulae stage and especially attempt to account for the plethora of wonderful shapes created by these processes.

Planetary Envelopes

Planetary nebulae have a very wide range of shapes that belie the usual perception of nice, round, ring-like objects. We shall later examine the morphological classifications recognized by visual observers; here we want to understand how such disparate forms are fashioned.

Heber Curtis first described the various morphological types in his 1918 study of planetary nebulae. His classifications of helical, annular, disk, amorphous and stellar have stood the test of time and have been the base subjects of re-classifications since, with one of the latest by B. Balick emerging as a simplified designation system of three types, namely round, elliptical and butterfly. Although such terms may not sound hyper-scientific, they more than adequately describe what is being observed. Most astronomers now use the system designated by Letizia Stanghellini of the Space Telescope Science Institute and her colleagues R. Corradi and H. E. Schwartz, which defined planetary nebulae by the following shapes:

1. Stellar
2. Elliptical
3. Bipolar
4. Point symmetric
5. Irregular

The advent of CCD imaging and the superb pictures from the Hubble Space Telescope have given astronomers new insights into how these different shapes are created by the same processes. Essentially the winds during the AGB phase create a circumstellar shell as we have seen, but the densest parts of the shell are found around the equatorial regions as the centrifugal forces there are a little higher than the rest of the star's envelope, allowing more material to be lost. When the hydrogen shell is puffed off in thermal pulsations, the expanding gases encounter this denser central "ring," or torus, around the star's equator and slow down at that point, while the rest of the escaping gases continue at their regular velocities. This then creates two expanding hemispheres of material and a 'waist' of slowly moving material, giving rise to the classic bipolar or helical shapes noticed in many planetary nebulae.

It is postulated, not without evidence, that all planetary nebulae are formed in this manner. The gases from the star are ejected as an expanding ellipsoid, which then becomes distorted due to interaction with circumstellar material. Classic examples such as the Ring Nebula, M57, and the Helix Nebulae, NGC 7293, are merely seen from the point where we are looking down directly onto their poles – the two hemispheres merging to make a 'ring' shape. If seen side on or from the equator, we would see the typical hourglass shape of a bipolar nebula.

Conversely, the outflow of gas may be collimated by magnetic fields or collected into a collimated jet of materials flowing from the poles that spreads and distorts as it hits the circumstellar shells ejected by the AGB star. Many proto-planetary nebulae have been observed to have such collimated outflows such as the Cygnus Egg and Minkowski 2–9. In all probability both mechanisms are in effect; it is merely a question of what point in the formation of a planetary nebulae does each mechanism becomes the most dominant feature at work.

There is some evidence that the type of nebula that results is tied to the mass and spectral type of the central star. A study of 160 planetary nebulae in the 1970s by W. E. Grieg found that bipolar nebulae have WC dwarfs at their centers and have a higher incidence of NII, OII and OI in relation to hydrogen lines in their spectra than other types. Corradi and Schwartz found a similar result in their 1995 study of bipolar nebulae, suggesting that such planetaries have a more massive, or intermediate mass, star as their progenitor. They also concluded that given the angular dimensions of the planetaries they studied, the bipolar planetaries were also more

advanced in age; younger planetaries just emerging from the proto-planetary nebula stage were more symmetrical and smoother in appearance, indicating an evolutionary path between young and old objects. Whether much of the foregoing is due to selection effects is yet to be seen. Needless to say, this is a fresh and exciting field of study.

There are some fantastic examples of bipolar nebulae available for amateur study, with M27, the Dumbbell Nebula, being the brightest of this class. Others include M76, the Little Dumbbell in Perseus; NGC 6302, the Bug Nebula in Scorpius; NGC 2440 in Puppis; and NGC 7008 in Cygnus. All are included in this book.

Other features that are also observable in some objects are the so-called micro-structures, or clumps of denser materials in some planetary nebulae. These are characterized by “ansae,” or rays, to use the old definition usually found in observational literature. These structures are known as FLIERs, or ‘fast, low ionization emission regions,’ usually seen as knotty inclusions in the shells of planetary nebulae, of which the structures forming the ‘rings’ in NGC 7009, the Saturn Nebulae, are among the best observed structures on a professional or amateur level. Occasionally a nebula can reveal some point symmetric structure, similar to an S-shape, which have the appellation BRET, or ‘bipolar rotating episodic jets,’ which are probably the result of magnetically collimated outflows, though FLIERs also may come under this description. The ‘furry hood’ of the Eskimo Nebula, NGC 2392, is due to inclusions termed ‘cometary knots’ and is evidence of interaction with the fast winds and the dust/gas ejected by the AGB star.

Such features can be difficult to see under direct viewing but may reveal themselves to a photograph or CCD image. Amateurs using such equipment may pick up such aspects in planetaries such as NGC 2371/2, NGC 7009 and NGC 4361 in Corvus.

How much of the planetary shell and its morphology is contributed by binary partner stars is as yet unknown. Considering the high percentage of stars of intermediate mass in binary partnerships (possibly 60%), it is important to account for the interaction between gas and binary partner in such emerging systems.

Binary Stars and Magnetic Fields

Stars in binary systems must go through the planetary nebulae stage at some point in their lives. It has always been assumed that single stars will inevitably go through the planetary nebulae process if their masses were sufficient enough, but over the last two decades doubts have been raised about the mechanisms of planetary nebulae formation from single objects. Conversely, astronomers did not know enough about the dynamics of binary systems to agree upon a model that could produce such nebulae.

Until recently, it was unclear how such interactions between a main sequence partner and an engorged giant star could lead to development of a planetary envelope as the mass transfer within the system was presumed to be via the Roche lobe interface between the stars, a gravitational point between the two stars where the extending envelope of the giant star would spill over into the gravitational domain of the other. This would then lead to mass sharing and the demise of any envelope that could develop to the planetary nebulae stage.

However, what if the separation of the stars was sufficient so that there would be little mass transfer due to distance, or if the interaction between the binary partner and the AGB stars slowed the orbital speed of the partner, but it did not spiral into the gravitational domain where Roche lobe transfer would be dominant? What if both stars were of small mass? It was important to model such systems there is evidence from several sources where planetary nebulae had binary stars at the center. How did the interaction between the stars contribute to the nebula?

Initial studies by Noam Soker in the late 1990s suggested that the binary separation of low mass red giant branch (RGB) stars and their partners would lead to mixing and possible coalescence of the two bodies as ejected materials from the RGB star caused orbital drag, resulting in the partner star spiraling inwards and sharing a common envelope.

Occasionally the cores would coalesce, too, depending on how long the RGB stage was and when the two stars began their interaction. Soker's calculations found that the stars would share a common envelope but remain as separate cores with distances between them of five or more solar radii. He further found that low mass stars would coalesce to form a single star if they had sufficient mass to spin up the envelope of the primary and thus ensure further gravitational interaction with the gas of the system. A star might even become an AGB star at this stage, but due to this coalescence, the resulting planetary nebulae may become an ellipsoid. This suggests that low mass stars could not form bipolar nebulae at all.

Stoker's work began to focus on the partners of intermediate mass stars where the two bodies remained separate. Although a partner could also be subject to tidal drag and spiral inwards in its orbit, if it remained separated by the end of the AGB phase then the orbital momentum of the system would contribute to the ejection of a bipolar nebula. His conclusions were that stars lower than 1.5 solar masses would not become bipolar planetary nebulae. Therefore, the wonderful bipolar nebulae we see in many instances come from the interaction of AGB stars and binary partners where the system collectively is made of intermediate or high mass stars.

These stars may still share a common envelope and thus the combined gases of the system will contribute to a large amount of material being lost in the equatorial plane of the system. This then forms a large torus of gas and dust that is slowly expanding. Once the ejection of material in a fast wind occurs, this wind is funneled through the torus to create the classic bipolar shape described earlier.

The mechanics of these systems are still ill defined, and work is ongoing in this fascinating field. It is essential to our understanding of planetary nebulae that we can tease out the contribution made by binary systems, comprehend their dynamics and explain how such interactions contribute to planetary nebula morphology. To date, many astronomers accept that bipolar nebulae are created by binary star partnerships, and observations, coupled to astrophysical modeling, provides vital clues. Recent studies by Soker (2004–2010) and others argue that single stars almost never become planetary nebulae, that binary systems are the key to their development rather than the single-star models used in former years. This has implications for our Solar System – perhaps the Sun will not end its life as a planetary nebula after all despite many years of belief that this was to be its end.

Increasingly astronomers are uncovering evidence that many planetary nebulae are a consequence of binary star partnerships. It is ironic that most of the modeling done on such systems has always involved single stars. Now that ideology is being overturned and a new era in planetary nebula research is dawning.

It is also unclear how large a part magnetic fields play in the production of planetary nebulae. Several examples such as NGC 6881, Minkowski's footprint and NGC 6537 appear to have outflows that resemble large magnetic sheaths or collimated patterns that resemble the electrical and magnetic phenomena known as Birkeland currents. Magnetic activity could certainly account for the appearance of BRETs and some FLIERs too; it is known that several isolated white dwarfs have very large magnetic fields. Recent studies by J. Nordhaus et al. have demonstrated that when two stars share a common envelope, then strong patterns are set up that result in an accretion disk forming around the heavier star. This disk then acts as a giant dynamo and increases the magnetic field strength of the system. Once the gaseous shroud of the nebula is lost, all that is left is a highly magnetized white dwarf.

Considering the ionization potential of the hot central stars of planetary nebulae, magnetic and electrical fields will play a part in the creation of gaseous outflows and streaming. Binary partnerships and magnetic fields, working together, probably account for the bipolar appearance of such nebulae.

Lifetimes of Planetary Nebulae

The expanding shells of luminous material that astronomers commonly image are very ephemeral on an astronomical scale. Most planetary nebulae will have faded into invisibility between 15,000 and 20,000 years after their production, and the materials composing them will become an inextricable part of the interstellar medium within a million years of their formation.

These materials are important in that they not only recycle hydrogen but also in that they enrich the ISM with carbon, oxygen, nitrogen and a host of other elements. These elements are also joined by exotic molecules such as polycyclic aromatic hydrocarbons (PAH), naphthalene, benzene, acetylene, hydrogenated amorphous carbon (HAC), methane and many more, which raise important issues as to the contribution of planetary nebulae to the materials necessary for life. Astronomers have found amino acids in the ISM such as glucose; the production of all these molecules from planetary nebulae begs the question of how such materials form chemical bonds under such rarefied conditions and whether they can be delivered to planetary surfaces. This is an interesting field of study that sadly is beyond the scope of this book.

Conclusion

As observers, we can revel in the beauty of such objects and consider the means of their construction. The astrophysical processes here described may form the basis of further studies for the reader should they so wish. Most, though, will probably be looking forward to discovering how such wonderful objects can be observed. This is the subject of our next chapter.

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