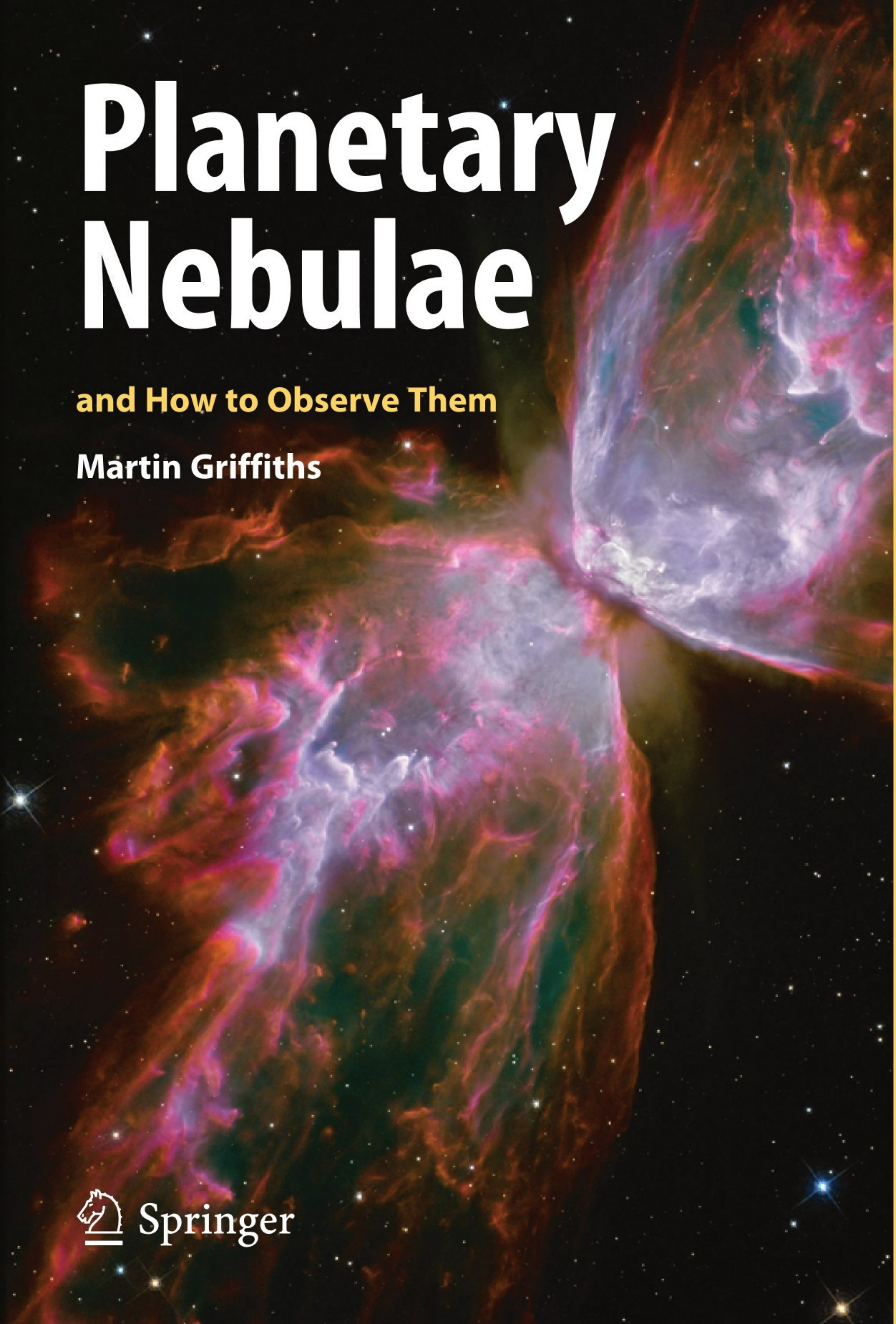
Planetary Nebulae

and How to Observe Them

Martin Griffiths



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inglism@sunysuffolk.edu

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Martin Griffiths
University of Glamorgan
Glyntaf, United Kingdom

ISSN 1611-7360
ISBN 978-1-4614-1781-1 e-ISBN 978-1-4614-1782-8
DOI 10.1007/978-1-4614-1782-8
Springer New York Dordrecht Heidelberg London

Library of Congress Control Number: 2011946227

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

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Preface

Planetary nebulae are among the diverse forms of astronomical objects available for amateur study and may be some of the most inspiring sights nature has to offer. Seldom is there a group with such a range of shapes, sizes and colors that have particular idiosyncrasies from object to object. Planetary nebulae are fascinating, beautiful and enchanting; what could be more wonderful than contemplating these small celestial objects, realizing that 1 day our Sun may join this band of heavenly entities? Their ethereal nature, short lifetime and range of forms make observing them a most pleasing study.

I have been entranced by them from a young age and can still remember my first look at the famous 'Dumbbell' Nebula, Messier 27, through a small refractor I had purchased from a friend. It was a puff of gas, blue-gray in color with a definite indentation on both sides nestled in a field of fainter stars, yet overflowing and seeming to envelop a few. I was hooked; since then, all planetaries have filled me with a delight that is not fully shared with other objects. Yes, I enjoy looking at faint galaxies, bright nebulae and majestic star clusters, but planetary nebulae are still my favorite objects and the ones I preferentially seek out while observing, no matter what telescope I am using. I am fortunate in that my life in both amateur and professional astronomy overlaps our increasing understanding of these lovely phenomena – an understanding that complements my frequent views of faint smudgy forms almost lost in the darkness of the midnight sky.

I hope that this volume will provide the tools necessary to start searching for these wonderful entities. It does not matter what the aperture of your telescope is or how frequently you observe, there are enough bright objects included in this book to please and delight most observers, and hopefully the illustrations will satisfy an armchair astronomer. I have attempted to strike a balance between easily visible objects that can be seen in any telescope or binoculars, to nebulae that are a direct challenge to those with large aperture equipment. With over 1,000 objects to choose from, the enclosed observing list represents just 10% of the number that could theoretically be seen or imaged, although it is fair to report that this 10% probably represents the best of the catalogues for amateur study.

I have also included an historical and physical analysis of planetary nebulae in order that the reader has a ready volume covering both observational and astrophysical aspects of the subject, which will give added understanding and impetus to the search. I find that when teaching students, the ability to see a faint or fuzzy blob of light is augmented by the fuller physical understanding of its intrinsic nature, leading to a greater appreciation for the object. How often have we shown someone a celestial delight we consider significant, only to have that observer disparage the eyepiece view? Observing any deep sky object with relatively small telescopes is not going to reveal a professional, observatory quality image, but this lack can be turned to our advantage by imparting some fore knowledge on the inherent nature of the item viewed, enabling an appreciation of cosmic distance, scale and power from our fleeting Earthly platform.

I have also included within the finder maps of some objects several additional planetary nebulae as they were shown in *Sky Map Lite*. These P-K nebulae may become challenge objects for observers wishing to go beyond the range of this book, and any information on them may be gleaned from the P-K catalogue included here or from sky chart programs or the Internet.

In the final analysis, I want observers to enjoy their experiences in hunting down these wonderful nebulae and discovering them for themselves. Our universe is not something that can be fully appreciated by superlatives, by numbers or formulae or by concentrating on specifics; it is something to be sensed, experienced, savored and valued. I especially feel this way when observing planetary nebulae. The great American poet Walt Whitman, conscious of such emotions penned:

When I heard the learned astronomer,
When the proofs, the figures, were ranged in columns before me,
When I was shown the charts and diagrams, to add, divide, and measure them,
When I sitting heard the astronomer where he lectured with much applause in the lecture-room,
How soon unaccountable I became tired and sick,
Till rising and gliding out I wandered off by myself,
In the mystical moist night-air, and from time to time,
Looked up in perfect silence at the stars.

(*Leaves of Grass* 1882)

I hope this small book will help one to grow in knowledge and appreciation of one striking facet of the universe around us.

Martin Griffiths BSc MSc FRAS
University of Glamorgan UK

Acknowledgements

This work has been the culmination of many years of research and practical activity in both amateur and professional astronomy. As such, it would be impossible to name all the people whom I have encountered who have provided encouragement and support for this venture.

However, I would like to thank the Faulkes telescope team for their encouragement and access to the Faulkes telescopes to provide the images, especially Dr. Sarah Roberts for supplying the illustrations of the EM Spectrum, the H-R diagram and the frontispiece photograph of Abell 39; the editorial staff at Springer for their helpful comments and suggestions and Ted Forte of the Astronomical League for his communication and encouragement.

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About the Author

Martin Griffiths is an enthusiastic science communicator, writer and professional astronomer. Over his career he has utilized history, astronomy and science fiction as tools to encourage greater public understanding of science. He is a recipient of the Astrobiology Society of Britain's Public Outreach Award (2008) and the Astronomical League's Outreach Master Award (2010). He also holds the League's Master Observer certificate and has written or contributed to over 100 published science articles for many journals.

He was one of the founder members of NASA's Astrobiology Institute Science Communication Group, which was active between 2003 and 2006; he also managed a multi-million-pound ESF programme in Astrobiology for adult learners across Wales between 2003 and 2008. Since then he has been involved in promoting adult education, assisting in the development of a new observational astronomy award at the University of Glamorgan and various other projects, including initial consultation on the setup of an observatory in Andalucia, Spain. He is a consultant to the Welsh government through his involvement with the Dark Sky Discovery initiative, enabling public access to dark sky sites in association with Dark Sky Wales, Dark Sky Scotland and Natural England.

Martin is a Fellow of the Royal Astronomical Society and a member of the Astrobiology Society of Britain, the European Society for the History of Science, the British Astronomical Association, the British Science Association, the Webb Deep-Sky Society, the Society for Popular Astronomy, and the Astronomical League. He is also a local representative for the BAA Campaign for Dark Skies and is a member of the Honourable Society of Cymmrodorion, dedicated to promoting the literature, science and arts of Wales.

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Chapter 1

A Short History of Planetary Nebulae

The beautiful objects we now recognize as planetary nebulae led invisible lives until the middle of the eighteenth century. On the evening of July 12, 1764, the French comet hunter Charles Messier observed a barely resolved blob of light in the constellation of Vulpecula. His note of the discovery shows that he dismissed it immediately after recording its position. After all, it was not the kind of object he was interested in:

> Nebula without star, discovered in Vulpecula, between the two forepaws, & very near the star 14 of that constellation, of 5th magnitude according to Flamsteed; one can see it well with an ordinary telescope of 3.5-ft [FL]; it appears of oval shape, & it contains no star.

It seems strange to us now that Messier turned to other objects without really examining this seminal discovery. His record shows that he noted what we now call Messier 27 in his catalogue of "objects to avoid while hunting for comets" as something that was relatively easy to see, but he spent little time examining it or he would have seen stars all across the surface of this singular nebula. Unfortunately, many of his contemporaries also paid as much attention to planetary nebulae as he. One cannot really hold them to account. They had no idea what such objects were, no idea of their size or distance or even the fundamental materials of which they were made. The only thing they could describe was their visual appearance and leave the rest to posterity.

Further Discoveries

Such nebulae may have aroused curiosity, but any further work on such types had to wait until there were further discoveries to enable comparison. However, they were not long in coming. Astronomer Antoine Darquier discovered an interesting round patch of light almost midway between γ and β Lyra in January 1779, and Messier independently discovered it later that month. Darquier described it as a "nebula between gamma and beta Lyrae; it is very dull, but perfectly outlined; it is as large as Jupiter and resembles a planet which is fading." This interesting description may have been quite suggestive, as we shall go on to see. Within a short time, Pierre Mechain discovered Messier 76 in September 1780 and Messier 97 was discovered by him a year later.

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Some of the best types of this intriguing astronomical class had now been discovered, yet they were merely catalogued. No one knew what kind of body they represented or what their true physical properties were.

In the summer of 1782, William Herschel, the German-born astronomer and discoverer of the planet Uranus began a systematic survey of the heavens in order to uncover and catalogue as many nebulae as possible with a view to determining their positions, distribution and possible make-up. One of the first objects in his new catalogue was found by him on September 7 of that year, a small extended object that he described as "very bright, nearly round *planetary* disk, not well defined." Clearly the term we now use for such objects was already in the minds of a few observers.

Herschel went on to classify 79 objects in his catalogue as planetary nebulae and gave then the appellation H IV. He arrived at the name we now use for such objects sometime in 1784 simply because they reminded him of the disk of the planet Uranus, which he remembered as a round greenish entity – very akin to planetary nebula. Most observers of the day expected such objects to become resolved into stars with greater magnification or with larger aperture telescopes. Even Herschel himself was initially convinced of their star-like qualities, and he was not inclined to consider them as true nebulae for some time.

NGC 1514 – Herschel's first planetary nebula.

However, the first hint of their true nature came to Herschel when he observed one of his own discoveries, the nebula we now call NGC 1514, on November 13, 1790. He described his observation succinctly as a "star of about 8th magnitude with a faint luminous atmosphere, of circular form and about 3 min in diameter. The star is perfectly in the centre and the atmosphere so delicate, faint and equal throughout that there can be no surmise of it consisting of stars, nor can there be any doubt about the connection between the atmosphere and the star," he wrote a paper for the Royal Society in 1791, which was published as "Nebulous Stars, properly so called," where he speculated that "[W]e therefore have a central body which is not a star, or have a star which is involved in a shining fluid of a nature totally unknown to us." The first evidence of the evolution between stars and nebula had been found. In 1800 the astronomer Friedrich von Hahn found the central star of M57 from Mecklenburg observatory and confirmed the relationship between stars and the strange vaporous atmospheres now being recognized as planetary nebulae.

Due to the lack of further analytical tools, the story of planetary nebulae did not advance much further than this. There were more discoveries of this type of object in the next century when Karl Ludwig Harding discovered the Helix nebula (NGC 7293) whilst compiling his great work *Atlas Novus Celestis* at Gottingen in 1820. William's son, John Herschel, discovered 16 planetaries in the southern hemisphere while cataloguing the southern sky at Feldhausen between 1834 and 1837. Both Frederick Struve and James Dunlop added further examples to the growing astronomical catalogues of the time until much of their work was amalgamated by J. L. E. Dreyer at the end of the nineteenth century into the *New General Catalogue of Nebulae and Star Clusters* (NGC). The total of known planetary nebulae had then risen to 95 entries, and a further 35 nebulae were listed in the supplement to the NGC, the Index Catalogue (IC).

The Nature of the Nebulae and Modern Catalogues

The real breakthrough in determining the nature of planetary nebulae arrived with the invention of spectroscopy by Kirchoff and Bunsen in the mid-nineteenth century. Their experiments with elements burned in a pure flame led to the formulation of three major laws of this discipline. The first law states that an "incandescent solid liquid or gas under high pressure (or temperature) emits a continuous spectrum"; the second is: "a hot gas under low pressure emits a bright line or emission spectra," and the third law states that "a continuous spectrum viewed through a cool low density [or temperature] gas produces an absorption spectra [dark lines]." The most important here is the second law, which states that a hot, low density gas produces an emission line spectrum. All it now required was an astronomer with a powerful enough telescope to be able to resolve such lines in the nebula.

The first person to do this was Sir William Huggins at Tulse Hill, London. On August 29, 1864, he trained his telescope and new spectroscope on the planetary nebula NGC 6543 in the constellation of Draco. Any argument over the true character of these heavenly objects faded away immediately. Huggins discovered a single emission line in the spectrum, which characterized the nebula as a hot gas.

A year later he used an improved spectroscope on the same nebula and discovered three emission lines in the spectrum, one of which he recognized as hydrogen, but he could not account for the other two. Thinking that he had discovered a new element, he christened the lines "nebulium" and wrote a paper entitled: "On the Spectra of Some Nebula" for the *Philosophical Transactions of the Royal Society*. The intensity of his research and the applications of the new scientific methods of photography and spectroscopy are brilliantly brought together by Huggins to explain the nature of planetary nebulae. He states:

> As expected for gaseous emission nebulae, the spectra of planetaries consist of emission lines, but 90 to 95 % of the visible light is emitted in one single emission line only! This *'Chief Nebular Line'* occurs at 5007 Angstroms, (now 500.7 nm) in the green part of the spectrum. It is in this circumstance that planetary nebula brightness differ significantly if determined with various methods: These objects are often considerably brighter (up to 2 magnitudes) visually than photographically, because the 5007 Angstrom line lies close to the highest sensitivity of the human eye. Also, as films are often less sensitive in the green part of the spectrum, it is difficult to get a good "true color" image of planetary nebulae. As this spectral line at 5007 Angstroms could not be assigned to a known element at the time of its discovery, I suspect that it must be emitted from a previously unknown substance.

Huggins was assisted in his discoveries by his wife Margaret, an avid astronomer in her own right who used the spectroscope to discover that gases of the Orion Nebula consisted of oxygen. Together they wrote an *Atlas of Representative Stellar Spectra* and speculated on the evolution of stars. So much had been achieved by Huggins that echoes down the years to anyone observing planetary nebulae today. He drew attention to the problems of colour definition, the difference between visual and photographic observations and left a legacy of further research on these wonderful objects that begged explanation of the chemical make-up and physical properties of planetaries. He had discovered that they were a form of emission nebula; now it became the province of others to uncover exactly what sort of astronomical object they were and the course of their evolution.

The twentieth century saw many advances in this field. Among the first was the Harvard Observatory survey of 1910 under the direction of Edward Pickering, where planetary nebulae were initially identified by placing a prism in front of the telescope, enabling the discrete spectral lines to be recognized. Margaret Mayall and Annie Jump Canon later discovered several others on photographic plates from the Harvard Observatory's southern telescope in Arequipa, Peru.

In 1918, a photographic study by Heber Curtis at Lick Observatory in California determined the position of many planetaries to be within the Milky Way Galaxy. His plates showed for the first time the enigmatic structure of planetary nebulae with double lobed structures, rays, ansae, blobs and other irregularities. Following on from the work of James Keeler at Allegheny Observatory and W. H. Wright at Mount Wilson, his spectroscope allowed him not only to obtain excellent spectra of planetary nebulae but also determine possible distances from the shift of the spectral lines of each object. However, due to their relative rarity, he put forward the suggestion that planetary nebulae were probably a very unusual stellar evolutionary path – a suggestion that we now know to be incorrect.

In 1922, Edwin Hubble, using data obtained with the 60- and 100 inch. telescopes at Mount Wilson, discovered a correlation between the magnitudes of the central stars of planetary nebula and their size. He then suggested that their enigmatic emission line spectrum was due to the nebula absorbing the continuous UV radiation from the central star. That same year, W. W. Campbell and J. H. Moore made high resolution spectroscopic studies of 43 planetary nebulae and discovered internal motions in 23 of them. They also noted that the spectral lines were split, which indicated nebular expansion.

A few years later in 1928 the astronomer Ira Bowen, working at the Mount Wilson observatories determined that the lines discovered by Huggins and named nebulium were, in fact, lines of the common element oxygen, but doubly ionized (known as OIII). Bowen also showed that the gaseous component of planetary nebulae were extremely rarefied; the OIII lines could only be produced as a result of what are now called forbidden line transitions, which result from interactions within extremely low density gases. Other lines in the emission spectra of planetaries were found to be those of nitrogen and neon that were also undergoing a forbidden line transition.

Around the same time, the American-born Argentinean astronomer Charles Dillon Perrine discovered that the observed splitting of the spectroscopic lines of planetary nebulae were due to two different velocities within the nebula – a blue shift indicating material moving toward the observer and a red shift indicating material moving away from the observer. He correctly interpreted this as a "bubble" of gases that were expanding away from a central source – or a central star. In 1927 the physicist Herman Zanstra at the California Institute of Technology determined a method of measuring the temperature of the central star of planetary nebulae and tied its ionizing effect to the atmosphere of expanding gases, the so called Zanstra method. His paper entitled "An Application of the Quantum Theory to the Luminosity of Diffuse Nebulae" was a seminal landmark in astronomer's attempts to understand how physical interactions at atomic scales played a large role in determining what type of astronomical object is observed.

Planetary nebulae as a group were becoming one of the most intriguing types of astronomical object and one of the most challenging to interpret. Studies before World War II by John C. Duncan working at Mount Wilson enabled astronomers to see that planetary nebulae underwent several stages of expansion. Duncan's photographs of extended filaments outside of the main envelope of M57, the "Ring Nebula," indicated previously unknown behavior of stars undergoing evolution to the planetary nebula stage. His studies led the way for further discoveries of planetary nebulae envelopes in the work of You-Hua Chu and George Jacoby at Kitt Peak Observatory in 1985 and the studies undertaken with the Hubble Space Telescope in the last two decades.

With the advent of the Palomar Observatory and its 48 inch Schmidt camera after World War II, the pioneering astronomer George Abell discovered many large planetary nebulae from the Palomar Observatory Sky Survey photographic plates in the 1950s. A decade later, Rudolph Minkowski used the 10 inch. telescope at Mount Wilson and discovered many small, distant planetary nebulae. Additionally, the astronomer and future astronaut Karl Henize, working at the Lamont-Hussey Observatory in South Africa, discovered a large number of previously unsuspected planetary nebulae in the early 1950s.

Contributions to our understanding of planetary nebulae were truly international. The Russian astrophysicist Ioseph Shklovsky noted the similarities between white dwarfs and the central stars of planetary nebulae in 1956, leading to further progress in our understanding of the evolution of stars and their relationship to planetary nebulae. What was needed was a catalogue that brought all these discoveries together and concentrated on this one type of object.

This defining catalogue of planetary nebula is the comprehensive 1967 work of Czech astronomers Lubos Perek and Lubos Kohoutek resulting in the *Catalogue of Galactic Planetary Nebulae,* affectionately known as the Perek-Kohoutek (P-K) catalogue, containing over 1,000 entries. Both astronomers broke with tradition and delineated planetary nebulae according to their galactic coordinates of latitude and longitude rather than right ascension and declination. The P-K catalogue coordinates seem a little strange at first, but the catalogue does contain the RA and Dec of each object also.

Many astronomers have added their names to the long roll of planetary nebula discovery over the course of the last 120 years, and it is not possible to go into every individual discovery in detail. The P-K catalogue and the more recent *Strasbourg-European Southern Observatory Catalogue of Galactic Planetary Nebulae* by Agnes Acker and colleagues remain the standard work on such objects, and over 1,500 planetaries are now known. Currently, David Frew and colleagues in Australia, working with the Macquarie/AAO/Strasbourg Hα Planetary Nebula Catalogue (MASH), are discovering nebulae in the proto-planetary stage and will add at least 1,000 more objects to modern catalogues.

After almost 250 years of observation, planetary nebulae remain one of the most surprising and beautiful of all celestial objects, and more and more of them are becoming visible as our understanding grows. One is forced to ask; what kinds of stars become planetary nebulae, and what are the physical parameters that create them?

Chapter 2

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.

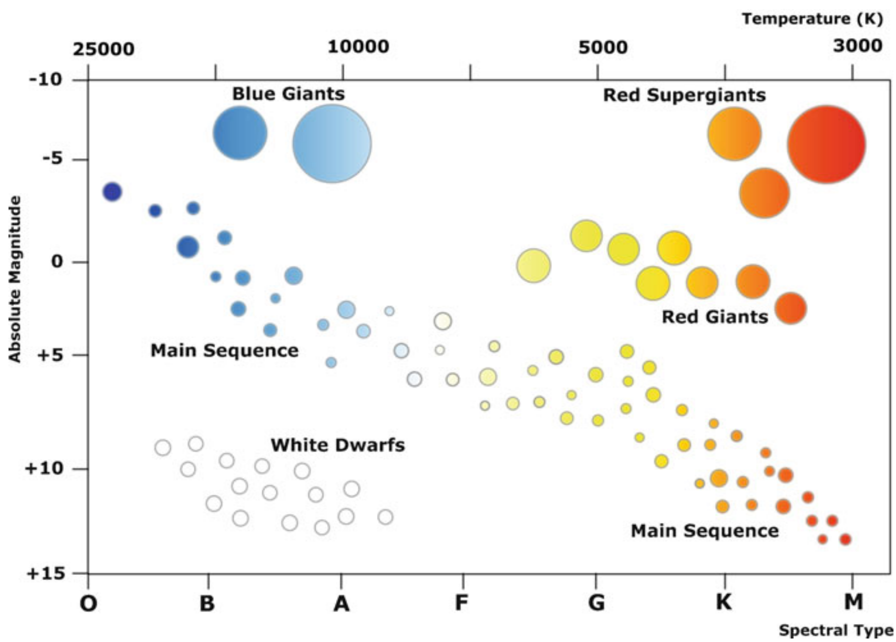
Once the temperature at the core of a proto-star becomes sufficient to fuse hydrogen into helium in the interior, the resultant flood of radiation away from the core and surface stop further aggregation of material, and within a few million

M. Griffiths, *Planetary Nebulae and How to Observe Them*, Astronomers' Observing Guides,
DOI 10.1007/978-1-4614-1782-8_2, © Springer Science+Business Media, LLC 2012

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 o 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, H_2O, CN, HCN, SiO, C_2H_2 (acetylene) and Fe_3O_4 (magnetite) in addition to nano-diamonds and fullerenes (C_{60}) 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