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Planetary nebulae

HISTORY

Before 1917

Several hundred years ago it became apparent to astronomers that other objects were present in the sky besides stars, planets and an occasional comet. These objects had a hazy or nebulous appearance, and it was for this reason that they were called nebulae. The nature of these objects was not clear and it took many years to discover that these objects do not form a homogeneous group, but that several very different classes of objects were being grouped together.

In the eighteenth century telescopes were small and imperfect; the images were not sharp and photography had not yet been discovered. This made it difficult to study the properties of nebulae. A controversy arose as to their nature: did the nebulae consist of many faint stars that were close together or did they consist of a luminous fluid? The regular appearance of the outer regions of globular clusters provided strong evidence for the former point of view, but the wide variety of shapes which were seen implied that some of the nebulae consisted of fluid or gas.

The first attempt to catalogue these objects was made by Charles Messier (1730–1817). He was a comet seeker and his motivation was to avoid confusion between the nebulous objects and comets. His catalogue, published in 1784, contained 103 entries. Four of these are now known to be planetary nebulae. A copy of this catalogue was given to the German-born English astronomer William Herschel (1738–1822), who immediately set to work to observe all these objects with his 30 cm and 48 cm telescopes. He concluded that most of the nebulae could be resolved into stars, and that the Milky Way could also be resolved into individual stars. He attempted to enlarge Messier's list: Herschel discovered 2000 new nebulae in seven years.

In a paper published in 1785, Herschel distinguished a class of nebulae that he considered to be distinct from the rest. He called them 'planetary nebulae' because they vaguely resembled the greenish disk of a planet. He found these objects intriguing. In a paper in 1791, he reported on an observation made the previous year: 'A most singular phenomenon! A star of about the 8th magnitude with a faint luminous atmosphere, of circular form. The star is perfectly in the centre, and the atmosphere is so diluted, faint and equal throughout that there can be no surmise of its consisting of stars; nor can there be a doubt of the evident connection between the atmosphere and the star.' Several examples are shown in Figure 1.

Herschel's argument that the nebulae did not consist of stars was simple. He was certain that the star at the centre and the nebula were associated because a chance coincidence of such a bright star so perfectly centred on the nebula was highly improbable. Thus, the star and the nebula are at the same distance. If the nebulosity is composed of stars they must either be very faint (assuming the central star to be ordinary) or, if they are normal stars, the central star must be of 'enormous size'. Herschel rejected both of these possibilities from which it followed that the nebula was not composed of stars.

Figure 1 shows photographs of a sample of planetary nebulae obtained by the Hubble Space Telescope. While all nebulae are different in detail, all have a generally similar morphology. They are usually symmetric, at least about one axis, and there is always a star at a centrally located position, clearly indicating a physical connection. Occasionally this star is so faint that it cannot be seen above the nebular background and an observer may conclude that it is absent. But careful observations, which suppress background light, will

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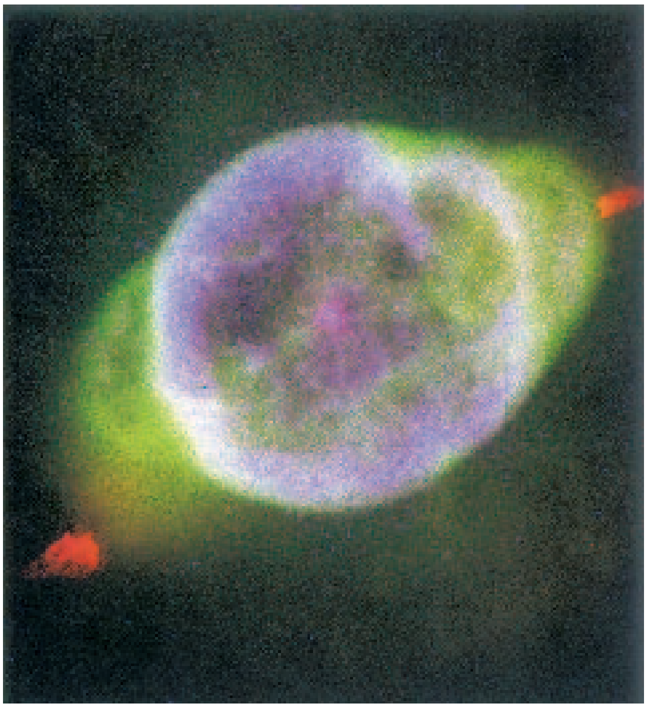

Figure 1 (a) The planetary nebula NGC 3242. The colours indicate the strength of certain lines as the image is a composite of three images of the nebula in different spectral lines, Note the strong red (N II) ansae or fliers at each end of the nebula. The central star is clearly visible. The matter appears to be dispersed in the form of a shell. This type of morphology is quite common.

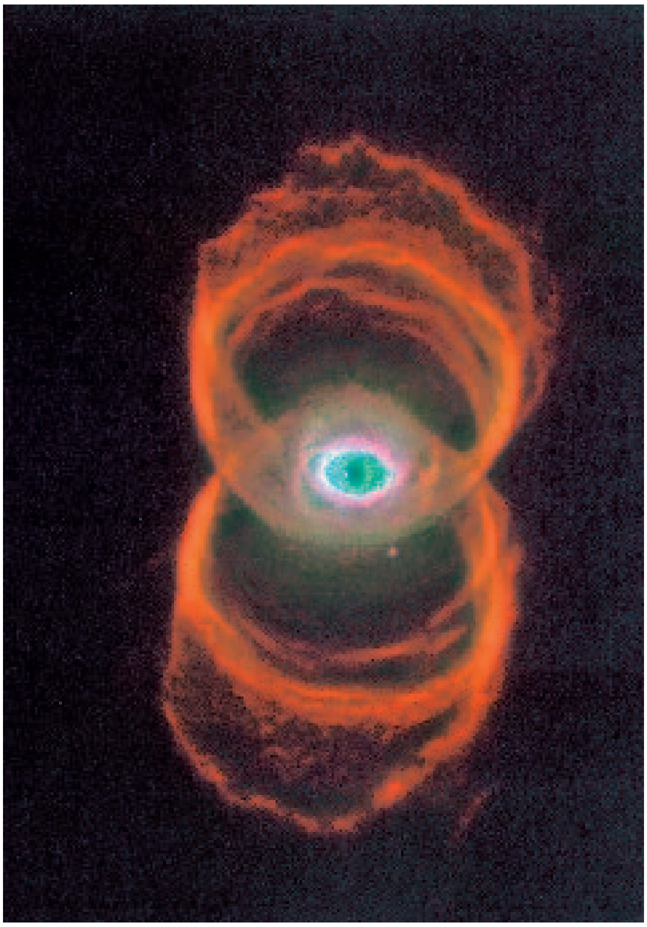

Figure 1 (b) The planetary nebula MyCnl 8. The morphology of this nebula is unusual. In addition, the central star appears to be offset from the centre. The reasons for this behaviour are unknown.

almost always render the star visible. Thus Herschel's conclusion that nebulae do not consist of stars (other than the central star) applies to the whole class of nebulae, and implies that all are in a similar stage of development or evolution.

By the middle of the nineteenth century further evidence became available which confirmed these nebulae as a separate class. The spectroscope had become available and was being used with telescopes to observe the Sun and stars. Joseph Fraunhofer (1787–1826) had discovered that the Sun emitted a continuous spectrum interspersed with sharp absorption lines. The planets showed many of the same features as the solar spectrum. The stars also showed a continuous spectrum, but each had its own set of absorption lines. In 1859 Gustav Kirchhoff (1824–1887), working in the laboratory of Bunsen in Heidelberg, discovered that certain elements in gaseous form emit lines at just the wavelengths of the solar absorption lines. In this way over 25 elements were identified in the atmosphere of the Sun.

William Huggins (1824–1910) was the first to examine a planetary nebula with a spectroscope. In 1864 he observed the bright nebula in Draco, NGC 6543. Huggins had been observing star spectra for over a year at that time, so that the spectrum he observed was completely unexpected. He found 'a single bright line only'. This bright line provided a means of distinguishing between starlight and gaseous light. The Great Nebula in Andromeda (as an example of 'spiral nebulae') was observed and showed a continuous spectrum indicating starlight. It was clearly a very different object than a planetary nebula. It was thus possible to distinguish gaseous nebulae from nebulae consisting of stars by using a spectroscope.

In 1865 Huggins used a spectroscope with higher resolving power, and was able to resolve the 'single' bright line into three individual lines. One line could be identified with a Balmer line of hydrogen (Hβ), while the other two stronger lines to the red remained unidentified. When it became clear that no element known in the laboratory would produce these lines, they were ascribed to a new element, nebulium. This was not the first new element named in this way. An unidentified line observed in the solar chromosphere during the eclipse of 1859 was ascribed to the then unknown element helium, while a line found in the solar corona during an eclipse 10 years later was ascribed to the element coronium. Helium was identified in the laboratory in 1895. The other two 'new elements' were identified only much later: nebulium in 1927 ([O III]) and coronium in 1939 ([Fe XIV]).

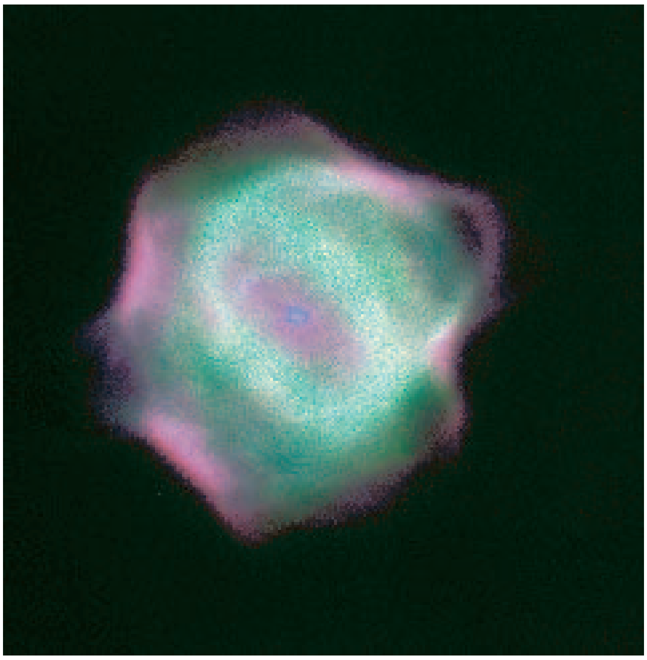

Figure 1 (c) The so-called Stingray nebula. This is a very young nebula in which the central star has been found to increase in temperature over a period of several years. Note the companion star, which is probably physically related.

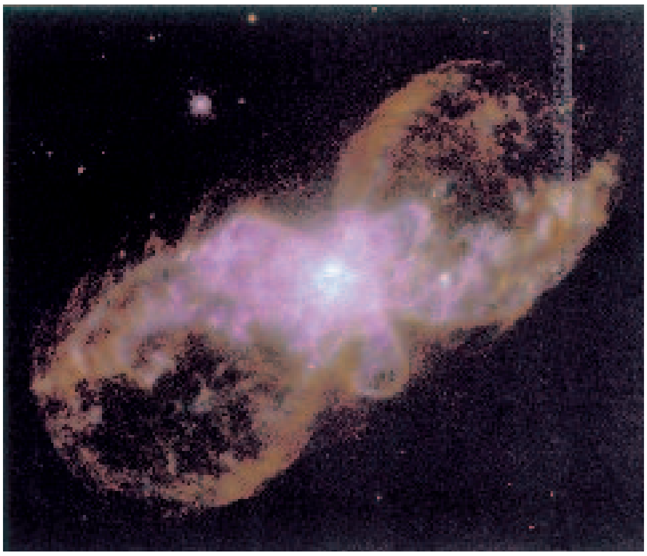

Figure 1 (d) Hubble 5. This is an example of a ‘bipolar’ planetary nebula. About 15% of all nebulae have this form. It is thought that the central stars of these nebulae are of higher mass than the average nebula, and that the nebulae have a higher nitrogen and helium abundance.

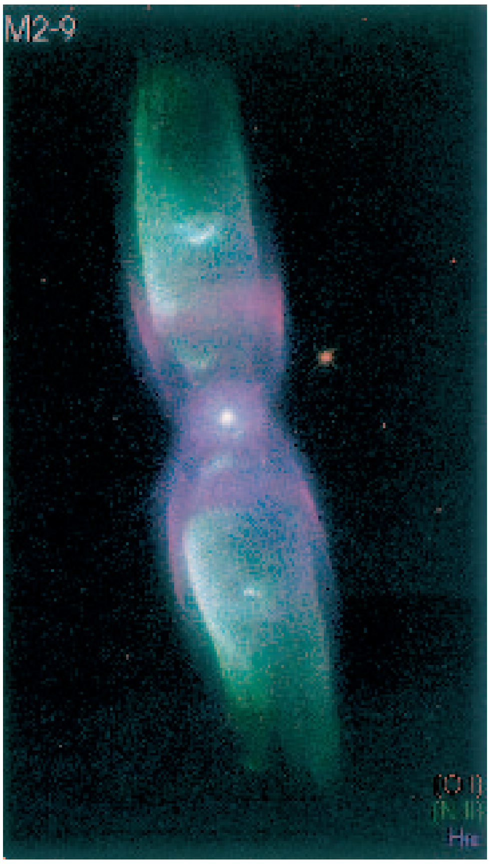

Figure 1 (e) The planetary nebula M2-9. The morphology of this nebula suggests that it is an extreme form of the ‘bipolar’ type, but the normal nitrogen and helium nebular abundance suggests that this is not true.

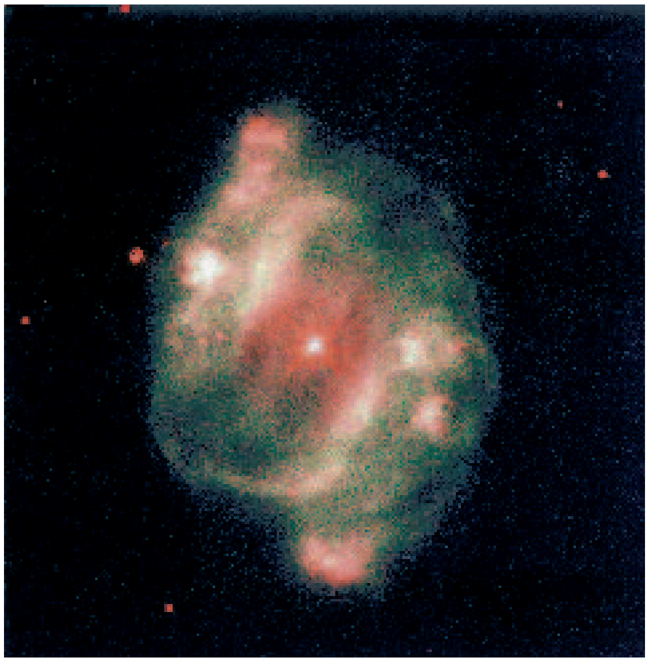

Figure 1 (f) The planetary nebula NGC 5307. An example of a nebula that does not show axial symmetry.

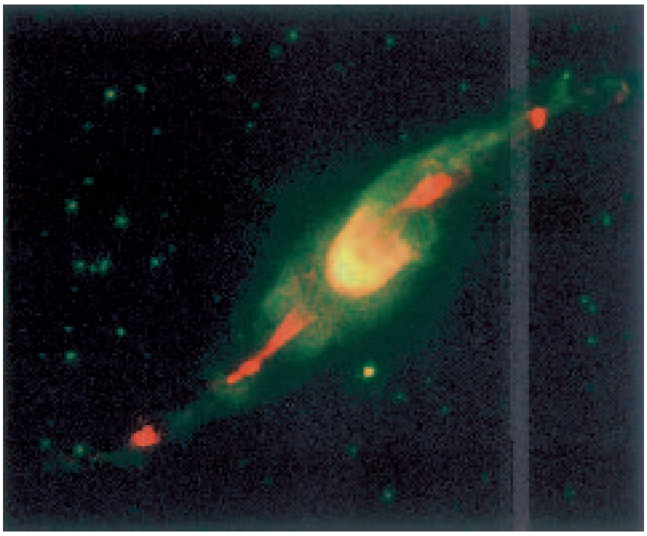

Figure 1 (g) He3-1475 is another very young nebula whose central star temperature has increased by a significant amount in the past 10 years. The origin of its unusual shape is not known.

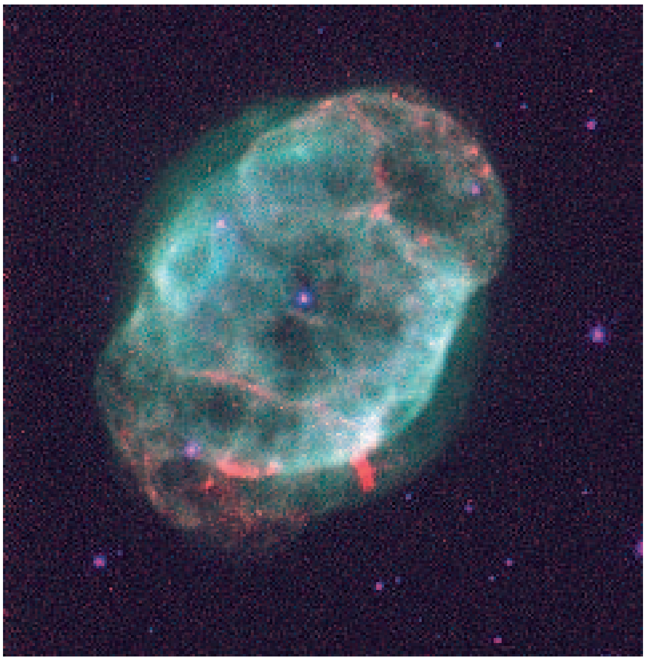

Figure 1 (h) The nebula 1C 4663. The elliptical morphology is quite common, as is the small-scale structure seen in the nebula. Only the central star is related to the nebula; the other stars in the field are foreground or background stars.

The work of Curtis and beyond

In 1918 Heber Curtis published an important paper in the *Lick Observatory Publications*. This is the first publication that attempts to define the status of planetary nebulae in terms of stellar evolution. The paper begins with a thorough summary of all the observational data available, including photographs and drawings of all 78 planetary nebulae then known and observable from the Lick Observatory. Curtis plotted the position of diffuse and planetary nebulae in the plane of the sky and showed that both were to be found close to the galactic plane. However, the 'spiral nebulae' were distributed uniformly except for a 'zone of avoidance' toward the galactic plane. When coupled with the spectroscopic information it was clear to Curtis that both diffuse and planetary nebulae were 'an integral part of our own galactic system' while spiral nebulae were 'very clearly a class apart – not only unconnected with our Galaxy but perhaps individual galaxies'.

On the basis of this information, it was possible to speculate on the place of planetary nebulae in stellar evolution. Planetary nebulae were rare objects: 'fewer than 150 are known in the entire sky. The relative proportion of planetaries to the total number of stars must be of the order of 10^{-5} or less. This minute percentage would seem to stamp the planetary nebula as an exceptional case, a sporadic manifestation of a path which has been rarely followed in stellar evolution.' The only alternative to this conclusion was to regard 'the planetary stage of existence as one of relatively very brief duration, through which the great majority of stars have long since passed.' Adopting the latter hypothesis, the lifetime in the planetary stage was calculable; less than 10,000 years. 'The very short life which must be presumed for the planetary stage of existence … does not seem inherently probable; it is as yet unsupported by any direct evidence.'

It is somewhat ironic that the 'direct evidence' actually existed. In the same volume in which the work of Curtis appeared was an article by Campbell and Moore which presented observations which are now used to show that planetary nebulae are actually about 10,000 years old. These astronomers obtained spectra at a higher resolution than was previously possible. They found evidence for important line broadening in 23 nebulae and in four cases the broadening was so large that the line was split. It is now known that this splitting is due to an expansion of the nebula with a velocity of about 20 to 30 km s^{-1}. Coupled with the size of the nebula this leads to an age of 10,000 years. But Campbell and Moore did not recognize the correct reason for the line splitting; they attributed it to a rotation of the nebula. The splitting was thought to be caused by matter on the outside of the nebula, which was supposed to be rotating more slowly than the emitting matter and absorbing the central part of the line.

Ten years later, in 1928, this interpretation was shown to incorrect when the nebulium lines were identified with forbidden line radiation. The absorption coefficient for these transitions is very low so that absorption as a cause

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