Making sense of dwarf-star evolution

A remarkable double white-dwarf star appears to confirm a mechanism by which binary stars lose angular momentum but suggests that the pair may yet spring to life a billion years from now.

IMAGES of planetary nebulae are among the most spectacular that telescopes can provide. There is a ring of glowing gas and, with luck, a small bright star at the centre. The ring of gas is not just a ring, of course, but a spherical shell that appears as a ring simply because the optical depth of a relatively thin shell is greatest at its extremities. 'Limb-brightening' is the technical term.

But how does a shell of glowing gas come to surround a star in such a way? The standard explanation is that planetary nebulae are produced late in the evolution of stars like the Sun. When the hydrogen fuel at the centre has been consumed to the tune of about 12%, the textbooks say, power production in the central core declines, the density at the centre increases and helium-burning begins in an even hotter inner core enclosed by a region still burning hydrogen. In other words, the power output of the star increases, its outer envelope expands under the influence of centrifugal radiation pressure and the star becomes a red giant, one whose luminosity is increased but whose external temperature is decreased.

That is only the first of many cataclysms. Soon, by the yardsticks of stellar evolution, even the helium core is diluted by the products of its own thermonuclear fusion (^{12}C and ^{16}O for example) to such a degree that specific power production begins to decline again. There may well be a hiatus during which the vastly expanded envelope of the star can no longer be sustained by radiation pressure, so that it begins to collapse, while the core begins producing thermonuclear energy by the C–N–O process, turning lightish nuclei such as those into ^{32}Si and eventually into ^{64}Fe.

The explanation for the cataclysms that occur in stars in this condition is simple: the evolution of the core must eventually become much more rapid than the response of the envelope can possibly be. So there will be a time when a collapsing envelope encounters an almost suddenly increased flux of outward radiation. The most likely outcome of that collision of contradictory events is that a shell of the red giant's outer envelope will be blown away.

But will it glow as a planetary nebula? That depends on what kind of object is left behind. There will be a star of some kind where the thermonuclear core used to be. Whether the blown-off shell keeps glowing depends on the surface temperature of the remnant star. If that should be, say, 50,000 K, the star will radiate in the ultraviolet and will excite even exotic spectral lines in the blown-off outer envelope. Then, indeed, the shell will glow. The remnant star will be a white dwarf, consisting mostly of helium at great density, say 10^9 kg m^{-3} or 1 tonne cm^{-3}, under which conditions the material is degenerate in the sense that its equation of state will be determined by quantum mechanics. Heat will be lost only slowly from such a star, chiefly because the surface area is only small.

Comparisons with supernovae are not irrelevant. They are also caused by the explosion of a star near the end of its tether. Again there is an expanding shell of glowing gas. The Crab nebula shows spectacularly how the remnant star may be a neutron star emitting recognizable radio pulses. But the original mass of a star destined to become a supernova is great enough to sustain the process of nucleosynthesis beyond the nuclei in the middle reaches of the periodic table, with the consequence that even the heaviest nuclei are synthesized.

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The planetary nebula Hen 1357. This image from the Hubble Space Telescope reveals an equatorial girdle of dense matter and polar holes where bubbles of matter have burst.

But supernova events are more spectacular than the throwing-off of planetary nebulae by several orders of magnitude. The surface temperature of the remnant neutron star, for example, will usually exceed 10^6 K. By the same test, the expanding shell moves outwards much faster than the glowing shell of a planetary nebula, whose velocity need not be much greater than the escape velocity from the surface of a red giant, itself much less than the escape velocity from the surface of a Sun-sized precursor.

The simple view of how white dwarfs come into being does not, however, account for the large proportion of them whose mass is small, perhaps less than half the solar mass. The difficulty is that progenitor stars smaller than the Sun will evolve more slowly, and that the Galaxy is probably not old enough for very small white dwarfs to have been formed by the standard mechanism. Is there some other way in which stars at the ends of their lives can shed substantial amounts of mass? That is the declared reason why T. R. Marsh from the University of Southampton has been looking for binary systems among the catalogues of white dwarfs (*Mon. Not. R. Astr. Soc.* **275**, L1–L5; 1995). And he has been lucky, finding a binary system in which each component is a white dwarf and in which there is clear evidence of motion in a tight orbit with a period of 3.47 hours.

Marsh's fellow-observers will no doubt be impressed by this demonstration of how it has been possible to extract from spectra taken with the William Herschel telescope on La Palma clear evidence that the H-α line from the star is split by the to-and-fro motion of the two stars in their orbit about their common centre. But the interest of the study is that it points to the way in which the double white dwarf may have come into being — and to what may happen to it.

Binary systems in general involve stars that differ from each other in mass or evolutionary state or both. That means that one will tend to accrete material from the other. But there are limits to the rate at which a star can accrete material, determined chiefly by considerations of angular momentum. The result is that material from the star losing material will spill over from within the region of tidal influence of the two stars; for a time they will each revolve about their common centre within this common envelope, but then the envelope will be expelled, carrying with it a substantial part of the angular momentum of the system, causing an abrupt shrinking of the orbit. In Marsh's view, this double white dwarf may already have suffered more than one of these episodes.

And what will happen to the system? The orbit is now compact enough to be a substantial source of gravitational radiation. In other words, even without a further common-envelope incident, the orbit will continue to shrink, so that the two white dwarfs merge with each other in roughly 2.5 × 10^9 years. And then the result may be a star that burns helium for a time. For white dwarfs, it seems, there may be life after death. **John Maddox**