Stellar Old Age: White Dwarfs, Neutron Stars, and Black Holes

In comparison to the human lifetime, stars are very long-lived phenomena whose changes in most cases are gradual and barely detectable. But even stars eventually grow old, and what happens then has been of increasing interest to astrophysicists and astronomers in recent years. Stars continue to evolve because they are constantly radiating energy. The loss is made up by the conversion of mass to energy in the thermonuclear fusion reactions that take place in the star's interior; but when all the fuel supply in the core has been converted to heavier elements, the core of the star begins to cool and contract. The decay processes are not well understood, but the final outcome is believed to be one of three different evolutionary end states—the white dwarf, the neutron star, or the black hole.

The white dwarf is possibly the most common end state of stellar evolution, and numerous examples have been observed since the first of these was discovered in 1915. The neutron star is a more unusual phenomenon whose existence was postulated almost 40 years ago but whose detailed structure is only now in the process of being understood. The 60-odd pulsars that have been identified since 1967 are now generally agreed to be examples of rotating neutron stars. The black hole is the least well understood and the strangest of the postulated stellar end states; and, although there is some indirect evidence for the existence of these objects, none have been identified. However, efforts by many scientists are bringing about rapid progress in understanding all three types of collapsed stars, and new observational results are adding to the information about their properties.

In fact white dwarfs, neutron stars, and black holes together contain so many new and varied phenomena that the study of these terminal stellar forms has become an interdisciplinary meeting ground for several ordinarily separate branches of physics, including astrophysics, general relativity, solid state physics, and elementary particle physics. For example, the superdense material found in neutron stars, according to a theory proposed by Malvin Ruderman of Columbia University, has properties such as regular crystal lattices, superfluidity, and superconductivity that are usually found only at very low temperatures. Mesons and other short-lived particles of the type produced in man-made accelerators are apparently stable in the core of neutron stars. The theoretical properties of black holes—as developed by John Wheeler and Remo Ruffini of Princeton University, Roger Penrose of Cambridge, and others—and the possibility that such objects exist has helped to change general relativity from an abstract field of physics into a discipline with direct astronomical significance.

Decayed stars differ markedly from ordinary stars, particularly in the nature of the forces that hold them up. For a star to exist, there must be an equilibrium in which outward forces balance the collapsing force due to the gravitational self-attraction of the stellar material. For ordinary stars with typical densities between 10^{-4} and 10 grams per cubic centimeter, thermal motions of the hot stellar gases provide the necessary outward pressure. White dwarfs are much smaller and more compact than ordinary stars, with radii of 10^4 kilometers—a factor of 10^2 smaller than the sun—and mean densities estimated from 10^4 to 10^8 g/cm^3. At these densities the stellar material is almost completely ionized and the pressure arises primarily from the motions of the dense Fermi gas of electrons, which, according to the exclusion principle of quantum mechanics, must move more rapidly as they are packed closer together. When matter is compressed even further to almost nuclear densities, electrons can combine with the atomic nuclei to form a "neutron gas," in which, for objects of about 1 solar mass, the pressure of the quantum mechanical motions of neutrons and nuclear repulsive forces are strong enough to balance gravity. The resulting neutron stars are believed to have radii of about 10 km and mean densities between 10^{11} and 10^{15} g/cm^3.

White dwarfs cannot exist with masses higher than a theoretical limit, estimated by Chandrasekhar, of about 1.2 solar masses. The corresponding upper limit for neutron stars is less certain, since it depends on which equation of state is used to relate density and pressure at nuclear densities, but it is believed to be less than 2 solar masses (Fig. 1). These estimates neglect rotation, which may have a stabilizing effect; work by Jeremiah Ostriker of Princeton University on white dwarfs and by Kip Thorne of the California Institute of Technology on neutron stars indicates that rapidly rotating stars could exceed these mass limits by as much as 50 percent. For a collapsing star whose core is more massive than these limits, gravitational forces are too strong to be resisted, and complete collapse into a black hole presumably takes place. When this happens, the stellar material appears to a distant observer to continue to contract forever, asymptotically approaching a limit known as the Schwarzschild radius—a distance of a few kilometers or more depending on the star's mass—at which point the geometry associated with that region of space is believed to be so curved that neither light nor mass can escape from the star. Density of the material in a black hole would exceed 10^{16} g/cm^3.

In the case of both the neutron star and the black hole, gravitational forces are so intense that theoretical calculations must include relativistic effects. According to Einstein's theory of general relativity, for example, light is deflected as it passes a massive object. A ray of light grazing the sun is deflected by about 10^{-4} degrees, and the same effect would be about 10^{-2} degrees in a white dwarf. In a neutron star, however, the deflection would be on the order of 10 degrees, as seen by a distant observer, while that same observer would see nothing at all in the case of a black hole because the deflection equals the radius of curvature of the surface itself.

The White Dwarf

White dwarfs are the best understood of the stellar end states, and the only one of the three types for which there has been any experimental confirmation of theoretical ideas. Detailed predictions of the size of a white dwarf for a given mass can be made based on assumptions about conditions in the star's interior. In a few cases white dwarfs have been found in binary star systems, so that, from observations of the orbit, both the mass and the radius of the star can be found. The observations agree relatively well with the predicted values, thus providing an experimental check of the assumptions about the star.

Although white dwarfs are often similar in appearance to other stars, they have luminosities roughly 5000 times smaller than ordinary stars of the same color. White dwarfs are usually identified from photographs of the sky taken over a long period of time. Those stars that are close to the sun are indicated on the comparative photographs by their apparently rapid movement relative to the fixed background. Those hot stars that are both near and faint must be very small and are likely to be white dwarfs.

The overall frequency of white dwarfs is about 3 percent of all stars, but, because of their faintness, data are known only for the region of space near the sun. Essentially all stars with masses less than the Chandresekhar limit are thought to become white dwarfs, but astronomers believe that some more massive stars can also end up in the white dwarf form. Red giants, for example, are sometimes described as white dwarfs surrounded by a large envelope; how the red giant loses its envelope and contracts to a dwarf is not known.

Once formed, however, the white dwarf appears to be a comparatively unexciting astronomical object—compared to neutron stars and black holes—that cools slowly and remains a stable, extremely dense body of material. Like neutron stars, however, white dwarfs can theoretically have very strong magnetic fields; and the discovery last year, by James Kemp and John Swedlund of the University of Oregon, of circularly polarized light that indicated a field between 10^6 and 10^7 gauss in one white dwarf has created new interest in these stars.

When ordinary stars contract, they may retain their magnetic field. Field strength increases inversely as the square of the radius, which is reduced by a factor of 10^2 during collapse to a white dwarf. Since normal stars have surface magnetic fields varying between about 1 gauss in the sun and 10^4 gauss in magnetic A stars, white dwarfs might have fields between 10^4 and 10^8 gauss, and the same process could produce even higher fields in neutron stars. According to a theory proposed by Kemp, there will be a net circular polarization in the continuum spectrum from stars with strong magnetic fields. In the presence of a magnetic field there is a shift in the wavelength of the circularly polarized radiation that is emitted from an atom when an electron changes energy levels. There is an analogous effect in free transitions—changes in the energy levels of free electrons such as are found in a plasma—in a magnetic field, and it is this latter effect that is believed to account for the observed polarization.

The initial observations showed a residual circular polarization of the light from the white dwarf in question of about 3 percent. Since then Roger Angel of Columbia University and John Landstreet of the University of Western Ontario have looked at a number of continuum spectrum dwarfs—those with no outstanding spectral features at all, rather than the emission and absorption lines that are common to most star spectra—and have discovered a second star with a circular polarization of 0.5 percent.

The evidence gathered so far has some confusing aspects. In the first star, for example, there are some absorption lines toward the violet end of the spectrum whose origin is a mystery to astronomers; they apparently cannot be accounted for in terms of the usual spectral positions of known elements.

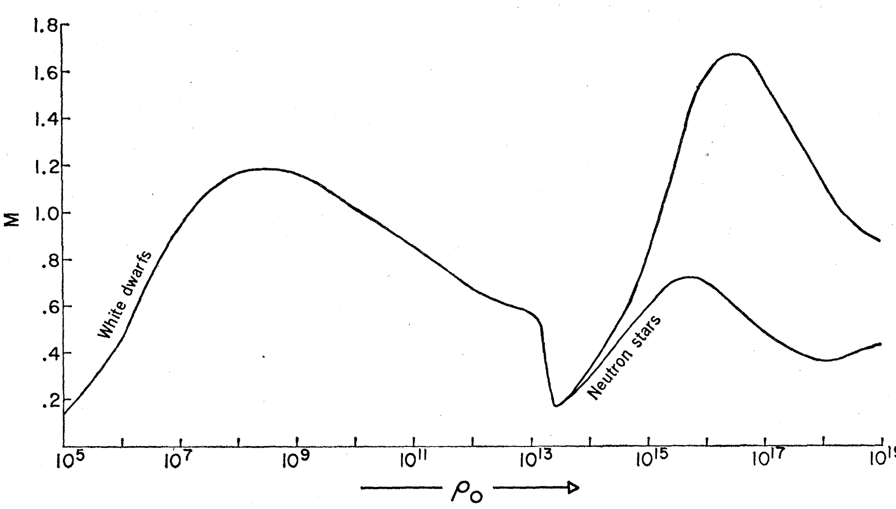

Fig. 1. The mass of collapsed stars in units of solar masses as a function of the central density in grams per cubic centimeter, as calculated by Remo Ruffini of Princeton University using the Harrison-Wheeler equation of state. The upper curve in the neutron star family is based on Newtonian physics, while the lower curve incorporates relativistic effects. [Adapted from *Physics Today*]

Despite the complications of shifted and unshifted lines—neither of which occur in the second star found by the Columbia team—astronomers view the observations as evidence that strong magnetic fields exist in at least a few white dwarfs. Out of 30 or 40 such stars surveyed, only 2 with strong magnetic fields have been reported so far, an indication that the ordinary white dwarf either evolved from a star with a weak magnetic field to begin with or lost some of its field during its collapse. Angel estimates that only about 1 percent of white dwarfs have strong fields. The white dwarfs with normal spectra do not appear to have fields in excess of 10^4 gauss, which is about the lowest that can be detected by looking for shifted spectral lines.

The strong magnetic fields in white dwarfs are not known to be responsible for any unusual astronomical phenomena, although a rapidly rotating dwarf of this type could possibly accelerate particles in space. This same mechanism is believed to be an important source of energy from neutron stars, which will be discussed in the second article of this three-part series.

—Allen L. Hammond