Stellar Old Age (II): Neutron Stars and Pulsars

Of the three postulated end states of stellar evolution—white dwarfs, neutron stars, and black holes—neutron stars have received the most attention in the last few years. In 1967 when astronomers first recorded radio signals from outer space that pulsed in a regular and rapid pattern, they speculated that the signals might have originated with intelligent life on planets near other stars. That possibility was quickly denied because of the lack of any planetary motion associated with the pulsar sources. But from the point of view of many astrophysicists the true nature of pulsars has turned out to be only slightly less exotic. They are now thought to be rotating neutron stars—a concept that previously was considered only a theoretical possibility. Recent research on neutron stars has focused both on their internal structure and properties and on the mechanisms by which the observed pulsar radiation is produced.

Pulsars were identified as neutron stars largely by the elimination of other possibilities. The faintness of the radio signals and the narrowness of the pulse width—typically about 20 milliseconds—imply that the signals are emitted by a source much smaller than any stars except white dwarfs and neutron stars. The signals also appear with clocklike regularity, and such periodic behavior in astronomy usually indicates that the source is either a pulsating or a rotating star, or a pair of stars in orbits that eclipse each other. Estimates of the periods expected from pulsating white dwarfs or neutron stars or from eclipsing binary systems of these collapsed stars are either too long, too short, or too rapidly changing to agree with the observed periods, which range from 0.03 to 4 seconds for the more than 60 known pulsars. The highest rotation rates conceivable for white dwarfs are not quite rapid enough either; neutron stars, however, are smaller and can rotate more rapidly, and this last possibility is now generally agreed to be the source of the observed signals. The observations show that the pulsar periods are gradually increasing, an indication that the stars are gradually losing energy to their surroundings and rotating more slowly, and that the most rapid pulsars may be the youngest.

Neutron stars are believed to be formed in supernova explosions when the core of a massive aging star implodes. Energy released during the implosion is thought to raise the pressure so high in the envelope of the aging star that it is blown away to form the nebula associated with a supernova. One well-studied pulsar is located in the Crab Nebula, which is known to be a remnant of a supernova explosion seen in A.D. 1054 by Oriental observers.

Neutron Star Structure

Considerable progress has been made in understanding the structure of neutron stars, but the theory is not far enough advanced to offer many specific predictions for comparison with observation. According to a structure proposed by Malvin Ruderman of Columbia University, the outermost layer of a neutron star consists of a rigid crust composed of heavy nuclei that are rich in neutrons. Because of mutual repulsion by short-range nuclear forces in the densely packed material, the nuclei are thought to be arranged in a crystal lattice. Deeper in the star, part of the material is in the form of free neutrons, so that the lattice is embedded in a sea of neutrons. Although the temperature in neutron stars is believed to be about 10^{10} degrees, the neutrons are so crowded together that they apparently behave like a frictionless superfluid as does helium below 2°K. The neutrons do not interact appreciably with the lattice and can move freely about. Further inside the star at about nuclear densities (3×10^{14} g/cm^3), according to the theory, the lattice melts and the nuclei disaggregate to form a uniform gas of neutrons and a few protons. At even higher densities—such as are expected in the core of the most massive neutron stars—mesons and other elementary particles may also be present.

One of the major concerns of physicists who are studying the structure of neutron stars has been the question of the appropriate equation of state to relate pressure and density under the extreme conditions that are believed to occur within the star. An accurate equation of state is of interest, among other reasons, in order to calculate the largest mass that can exist as a neutron star without collapsing to a black hole. An approximate equation of state can be calculated from the Pauli exclusion principle without knowing the forces between nucleons, but more accurate results depend on knowing these forces. A variety of methods—in some cases yielding differing results—have been tried. A group headed by Al Cameron at Yeshiva University has developed an equation of state based on information about nucleon-nucleon interactions from scattering experiments. A second approach followed by several groups, including that of Hans Bethe at Cornell, calculates an equation of state by means of semi-empirical formulas based on what is known about the binding energy of nuclear matter.

A third method combines both the scattering data and the information on binding energies; based on nuclear matter theory or modifications of it, this approach is thought by many physicists to hold the most promise. At the recent New York meeting of the American Physical Society (APS), Gordon Baym of the University of Illinois reported new calculations with this latter method, which he has done in conjunction with Christopher Pethick and Bethe. The results indicate that a lattice of nuclei will be present in the star's interior over a wide range of densities. The results also give a mass limit for neutron stars of about 2 solar masses, somewhat higher than earlier results reported by a group at the Massachusetts Institute of Technology. Despite uncertainty about details, however, there appears to be generally good agreement among theoreticians concerning the proposed structure for neutron stars.

Observational evidence that reinforces the theoretical picture has been obtained by careful timing of the signals received from pulsars. In at least two pulsars, the repetition rate of the signals—and hence presumably the rate of rotation—has been observed to increase suddenly, possibly as a result of starquakes in the rigid crust; then the star gradually approaches its former state of rotation over a period of weeks, and, in some cases years. This length of time is such that the frictional drag on the crust from the interior must be very weak, according to work by Ruderman and Dave Pines of the University of Illinois; if the crust was strongly coupled to the motion of the star's interior, the adjustment period should be so short that it could not be observed. Hence these observations seem to support the idea of a rigid crust rotating rather freely on the internal sea of superfluid neutrons.

Several substantial difficulties must be overcome before theories of neutron star structure are specific enough to permit quantitative comparison of predictions and observations. For example, a more detailed description of the coupling between the crust and the interior is needed, but neither the effective viscosity of the neutron superfluid nor its motions, which may be turbulent, are known. Likewise, methods of calculating the rheological behavior of the crust—how it strains, creeps, or cracks—need to be developed.

Magnetic Field Effects

The region exterior to a rotating neutron star also contains many complex phenomena associated with the effects of the star's strong magnetic field, and astrophysicists have made some progress in understanding these phenomena and the mechanisms which produce the pulsar radiation. Magnetic field strength increases inversely with the square of the radius during the collapse of a star whose field is not lost. Since neutron stars are about 10^5 times smaller than ordinary stars, they might have fields as high as 10^{12} gauss. The field is thought to be anchored to the highly conducting solid crust of a neutron star, and hence presumably rotates with the same period as that of the star. This spinning magnetic field is thought to emit magnetic dipole radiation. Far from the star, according to a theory proposed by Jeremiah Ostriker of Princeton University and James Gunn of the California Institute of technology, this radiation would appear as outward traveling electromagnetic waves that could carry off energy and angular momentum and thus account for the gradually increasing period of the pulsars. Their calculations, based on the observed period for the Crab pulsar and its rate of change, give an estimate of about 10^{12} gauss for the magnetic field.

Near the star things may be more complicated due to the presence of a plasma-filled region known as a magnetosphere—as Peter Goldreich and William Julian of the California Institute of Technology have pointed out. Far from the star, however, their model predicts many of the same properties that would occur in the absence of the magnetosphere.

The physical origin of the pulses is still uncertain. Goldreich has suggested that a small wobble in a spinning neutron star—one which might arise from small distortions in the rigid crust—would be sufficient to cause the misalignment of the mechanical axis of rotation and the magnetic axis and might be responsible for the periodic signals. A variety of mechanisms for producing the actual radiation have been proposed, most of which assume that charged particles are emitted from the magnetic poles of the star and are accelerated by the changing electromagnetic field; the energetic particles are then thought to give off the observed radiation. Although only radio frequency signals have been detected from most pulsars, the source in the Crab Nebula has been observed in the optical and x-ray regions of the spectrum as well, and a group of astronomers at the University of Bristol have recently announced detection of gamma radiation from the Crab. Most of the pulsed radiation from the Crab is in the x-ray region, which seems to support the idea proposed independently by Franco Pacini and Tom Gold of Cornell and others to the effect that energetic electrons which give off radiation in the magnetic field of the star are the source of the observed pulses.

However only a small amount—typically 0.1 percent—of the energy output calculated for rotating neutron stars is pulsed. Most theories assume that the bulk of the energy is given off in the form of energetic particles and fields. Gunn and Ostriker, for example, propose that charged particles from the star, which are propelled by the outward traveling electromagnetic waves, eventually become uncoupled from the waves. When this happens the magnetic field can cause them to radiate. Electrons accelerated in this manner by the Crab pulsar, for example, can apparently reach energies of 10^{14} electron volts, an energy high enough to produce the observed x-radiation from the nebula surrounding the star. In fact it appears very likely that the energy source for the characteristic bluish light emitted by the central part of the Crab Nebula—radiation whose unusual properties are thought to be due to energetic electrons and magnetic fields and whose origin has been a mystery to astronomers for years—is the rotating neutron star located there. This possibility had been proposed by John Wheeler of Princeton University and Pacini even before the discovery of pulsars. There is good quantitative agreement between the energy input required to make the nebula glow and the energy output calculated from the slowing down of the pulsar. Hence studies of pulsars have apparently helped to solve an old astronomical problem as well.

If pulsars can accelerate electrons, they can presumably accelerate protons and other charged particles as well. Hence they may be the source of the high-energy cosmic rays—another longstanding astrophysical problem—that strike the earth from all directions and are believed to pervade interstellar space. Cosmic rays with energies as high as 10^{20} ev have been observed. According to estimates presented at the New York APS meeting by Ostriker, newly born pulsars are capable of producing cosmic rays with energies up to 10^{21} ev. Supernova explosions in this galaxy occur about once every 30 years, and from this pulsar birth rate he calculates pulsars could produce more than 10^4 times the observed energy density of cosmic rays. The implication is that many of these energetic particles eventually escape from the galaxy. Ostriker speculates that the resulting cosmic ray gas may be a major constituent of intergalactic space.

Although it remains to be seen whether the spectra of energies and chemical species which are observed in cosmic rays can be produced by rotating neutron stars, it seems clear that these collapsed stars can be an important cosmological source of energy in the form of charged particles and electromagnetic radiation. In fact, several groups are investigating whether the extremely distant but energetic objects known as quasars might be either a collection of pulsars and supernova remnants or a giant rotating magnetic body with properties very similar to pulsars.

Neutron stars have the distinction of being one of the few astronomical phenomena that have been predicted long before discovery—in this case almost 40 years—but black holes may be the next. Some of the recent theoretical research on these mysterious end states of stellar evolution and some indirect evidence for their existence will be the subject of the last of this series of three articles.—ALLEN L. HAMMOND