Neutron Stars*

Gordon Baym and Frederick K. Lamb
Department of Physics, University of Illinois at Urbana-Champaign, 1110 West Green Street, Urbana, Illinois 61801
(April 8, 2005)

Neutron stars are highly condensed stellar objects produced in supernova explosions, the end point in the evolution of more massive stars. Neutron star masses M are in the range of 1-2 times that of the sun ($M_\odot$), whereas typical radii are only 10-12km; the matter they contain, primarily neutrons, is thus the densest found in the universe today. The average interior density is greater than that in a large atomic nucleus, $\rho_0 = 3 \times 10^{14}$g/cm^3. (By comparison, white dwarf stars, which are of similar masses, have radii of at least several thousand kilometers, and central densities in the range of $10^5 - 10^9$g/cm^3.) Support against gravitational collapse in a neutron star is provided by the quantum-mechanical Fermi (or zero-point) pressure of the neutrons and other particles in the interior, in the same way that white dwarfs are supported by electron zero-point pressure. (Ordinary stars, on the other hand, are supported by thermal gas pressure.)

Neutron stars were first proposed by Baade and Zwicky in 1934 in their pioneering paper on supernovae, and considerable theoretical work on their properties, beginning with calculations by Oppenheimer and Volkoff in 1939, was carried out prior to their actual observation. It was not until the discovery in 1967 by Bell and Hewish of radio pulsars – stars whose radio emission appears to blink on and off – and their identification by Gold as rotating neutron stars, that the existence of neutron stars was established. Since that time neutron stars have become cosmic laboratories for testing fundamental physics, including relativistic theories of gravity and the properties of matter at extreme densities. Neutron stars also play a crucial astrophysical role as the objects underlying a wide variety of highly energetic compact radio, x-ray, and gamma-ray sources. Radio pulsars are rotation-powered, are found both in isolation and in binary star systems, and are observed to emit radiation at all frequencies from radio to optical to gamma rays. Neutron stars are also found in luminous compact x-ray binaries in which they accrete matter from a companion star. About 1500 neutron stars have so far been detected in the galaxy as radio pulsars, including about 125 such pulsars with millisecond periods. More than 200 accretion powered neutron stars have been detected in x-ray binary systems; about 50 are x-ray pulsars and a similar number produce intense x-ray bursts powered by thermonuclear flashes.

The astrophysical energy source of neutron stars, some 10 times as powerful as thermonuclear burning, is their immense gravitation. The gravitational acceleration ($g = GM/R^2$, where G is Newton's gravitational constant) at the surface is about 10^{11} times that on Earth; gravitational tidal forces would make it impossible for any normal object larger than about 10cm to reach the surface of a neutron star without being torn apart. The gravitational binding energy GmM/R of a particle of mass m at the surface is about one-tenth of its rest energy mc^2. (Nuclear binding energies are, in comparison, at most 0.9% of the rest energy of matter.) The energy emitted by neutron stars in x-ray binary systems comes primarily from the gravitational energy released by matter accreted onto the neutron star from its companion star; nuclear energy contributes a few percent. The energy source of rotating pulsars – the kinetic energy of rotation of the neutron star – also comes from the release of gravitational binding energy, for as the stellar core in a supernova collapses under gravity to form a neutron star, conservation of angular momentum requires that its rotation rate and rotational energy increase. Other neutron stars gradually release gravitational energy stored as magnetic or thermal energy.

Neutron stars characteristically are strongly magnetized, with surface magnetic fields ranging from 10^6G to 10^{15}G. The slowing down of pulsar rotation implies magnetic fields of order 10^{11}G to 10^{15}G. The rapid rotation of such fields is important in generating relativistic particles and radio emission. Plasma accreting onto neutron stars in x-ray binary systems is channeled to the magnetic poles by fields ranging from 10^8 to 10^{13}G.

At birth, the interior temperature of a neutron star is about 10^{11}K, and within the first few days it cools by neutrino emission to less than 10^{10}K. Throughout most of its early life, the interior temperature is in the range $10^8 - 10^9$K and the surface temperature is one-tenth or less of the interior temperature. The hot surface typically radiates x-rays. X-ray satellites such as Chandra and XMM Newton have detected x-ray emission from

*To be published in *Encyclopedia of Physics 3rd ed.*, R.G. Lerner and G.L. Trigg, eds., Wiley-VCH, Berlin. Research supported in part by NASA grant NAG 5-12030, NSF grants PHY 03-55014 and AST 0098399, and the Fortner Endowed Chair at the University of Illinois.

cooling stars but the emission process and the size and structure of the emitting regions are not as yet sufficiently understood to infer accurately neutron star surface temperatures and radii from these measurements.

The matter inside neutron stars has a relatively low temperature compared with its characteristic microscopic energies of excitation, typically of the order of MeV (million electron volts). Furthermore, nuclear processes in the early moments of a neutron star take place sufficiently rapidly compared with the cooling of the star that the matter essentially comes – via strong and electromagnetic interactions, as well as weak interactions (which transform protons into neutrons and vice versa) – into its lowest possible energy state.

The cross section of a neutron star interior is shown in Fig. 1. The density of matter increases with increasing depth in the star. Beneath an atmosphere, compressed by gravity to less than 1cm height, is a crust, typically $\sim$1km thick, consisting, except in the molten outer tens of meters, of a lattice of bare nuclei immersed, as in a normal metal, in a sea of degenerate electrons. The matter in the outer part of the crust is expected to be primarily ^{56}Fe, the end point of thermonuclear burning processes in stars.

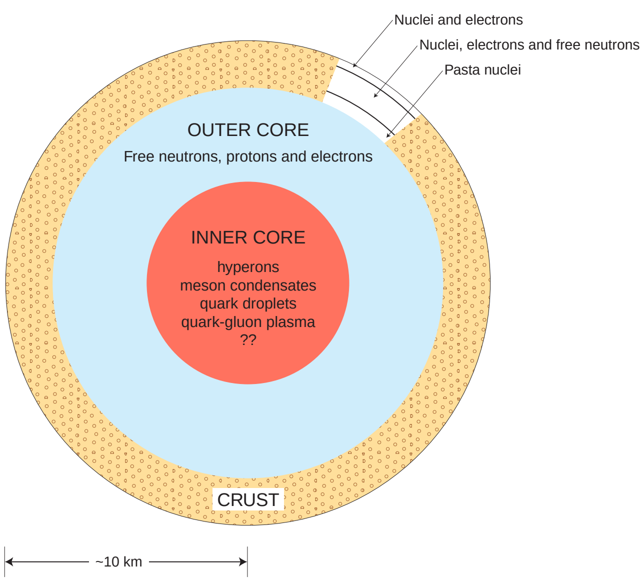

FIG. 1. Schematic cross section of a neutron star, showing the outer crust consisting of a lattice of nuclei with free electrons, the inner crust which also contains a gas of neutrons, the nuclear "pasta" phases, the liquid outer core, and the possibilities of higher-mass baryons, Bose-Einstein condensates of mesons, and possible quark matter in the inner core. (Figure kindly drawn by Michael Baym.)

With increasing depth, the electron Fermi (or zero-point) energy rises. Beyond the density 8×10^6g/cm^3, it is so high ($>$ 1MeV) that ^{56}Fe can capture energetic electrons. In the capture process, as occurs during the formation of the neutron star in a supernova, protons in nuclei are converted into neutrons via the weak interaction $e^- + \mathrm{p} \rightarrow \mathrm{n} + \nu$. The produced (electron) neutrino ν escapes the nascent neutron star, lowering the energy of the system. (Neutrinos generated in the formation and neutronization of the neutron star are eventually responsible for ejection of the mantle in the supernova.) The matter becomes more neutron rich and rearranges into a sequence, with increasing density, of increasingly neutron-rich nuclei, reaching nuclei such as ^{118}Kr at a mass density $\rho_\mathrm{d} = 4.3\times10^{11}$g/cm^3. The uncertainties in the actual nuclei present reflect current uncertainties whether the shell structure of highly neutron rich nuclei is determined by the same *magic numbers* (e.g., 82 neutrons) that determine the shell structure of normal nuclei. The nuclei present deep in the crust, although unstable in the laboratory, cannot undergo beta decay via the inverse reaction $\mathrm{n} \rightarrow \mathrm{p} + e^- + \bar{\nu}$ (where $\bar{\nu}$ is an anti-(electron) neutrino) because the electron would, by energy conservation, have to go into an already occupied state, a process forbidden because electrons obey the Pauli exclusion principle. Beyond the density ρ_d, called the "neutron drip" point, the matter becomes so neutron rich that not all the neutrons can be accommodated in the nuclei, and the matter, still solid, becomes permeated by a sea of free neutrons in addition to the sea of electrons. Then at about a density $\sim \rho_0/3$, spherical nuclei become unstable, as in fission, and the matter proceeds through a sequence of rather unusual structures, termed "pasta nuclei," with the nuclei first becoming rod-like and then laminar, with pure neutrons filling the space between. The pure-neutron plates become thinner; eventually the neutrons form rods, and then spheres, with the between regions containing proton-rich matter. Remarkably, over *half* the matter in the crust is in the form of these non-spherical configurations. Finally, at a density of about ρ_0, the matter dissolves into a uniform liquid composed primarily of neutrons with a few percent protons and electrons and a smaller fraction of muons. The neutrons are most likely superfluid and the protons superconducting; the electrons, however, are normal.

The states of matter at high pressures deep in the interior are less well understood. With increasing density heavier baryons can live stably in the star. Several interesting phenomena are possible (see Fig. 1). One is that pi mesons are spontaneously produced and form a superfluid "Bose-Einstein condensed" state; such condensation would greatly enhance the cooling of neutron stars by neutrino emission. The matter may similarly undergo an analogous "kaon condensation." At ultrahigh densities, where the nucleons are strongly overlapping, matter is expected to dissolve into "quark matter," in which the quarks that make up the baryons become free to run throughout. Quark matter most likely first appears as droplets in a sea of nuclear matter at densities of order several times ρ_0; a core of bulk quark matter, which would be present at higher densities, would also enhance neutron star cooling, but whether the transition to bulk quark matter is actually reached in neutron stars remains uncertain.

The structure of neutron stars, including their radii as a function of mass, and the range of masses for which they are stable, is determined by the equation of state of the matter they contain. A knowledge of the maximum mass $M_{\max}$ that a neutron star can have is important in distinguishing possible black holes from neutron stars by observations of their masses. The uncertainty in the present theoretical limit, $M_{\max} \sim 2.5 M_\odot$, calculated on the basis of physically plausible equations of state, reflects our uncertainty of the properties of matter at densities much greater than ρ_0.

The ever-growing body of observational information on neutron stars provides increasingly stringent constraints on the structure of neutron stars and the properties of neutron star matter. The neutron stars detected in relativistic double neutron star binary systems have masses between 1.33 and 1.45 $M_\odot$, whereas those of some neutron stars in other compact binary systems are at least 1.6 to 1.7 $M_\odot$. The masses of neutron stars in x-ray binary systems can be estimated by combining optical and x-ray observations of these systems; the estimated masses range from about one to $\sim 1.9 M_\odot$. Measurements of the frequencies of the kilohertz quasi-periodic x-ray oscillations of more than 20 accreting neutron stars potentially constrain simultaneously the masses and radii of these stars. Information on the moments of inertia of neutron stars can be extracted from measurements of the behavior of their spin periods and luminosities over time and from precision measurements of general relativistic spin-orbit coupling in double neutron star binary systems. In addition, sudden speedups and smaller fluctuations in pulsar repetition frequencies provide clues to the internal structure of neutron stars, and support the idea that the interior is superfluid.

See also: Fermi–Dirac Statistics; Pulsars; Stellar Energy Sources and Evolution.

G. Baym and C.J. Pethick, *Annu. Rev. Nucl. Sci.* **25**, 27 (1975); *Annu. Rev. Astron. Astrophys.* **17**, 415 (1979); H. Heiselberg and V.R. Pandharipande, *Annu. Rev. Nucl. Part. Sci.* **50**, 481 (2000). (On properties of matter in neutron stars; extensive references.) (A)

C.L. Fryer in *The neutron star–black hole connection*, Proc. NATO Advanced Study Institute, NATO science series C, Vol. 567 (C. Kouveliotou, J. Ventura, and E.P.J. van den Heuvel eds.), Kluwer, Dordrecht, 2001. (On formation of neutron stars in supernovae.)

F.K. Lamb and W. Yu, in Binary Radio Pulsars, ASP Conference Series no. 328 (F. Rasio and I. Stairs, eds.), ASP, San Francisco, CA, 2005. (Summarizes current knowledge of neutron star magnetic fields and spin rates, in a useful volume on the properties of x-ray and radio pulsars and their use in testing relativistic theories of gravity.)

W.H.G. Lewin and M. van der Klis (eds.), *Compact Stellar X-ray Sources.* Cambridge Univ. Press, 2005. (Overview of the properties of neutron stars in x-ray binary systems.)

A.G. Lyne and F. Graham-Smith, *Pulsar Astronomy*, 3rd. ed. Cambridge Univ. Press., 2005. (Describes supernovae, x-ray binary systems, isolated and binary radio and x-ray pulsars, and x-ray bursters.)

D.J. Nice, E.M. Splaver, & I.H. Stairs, in *Young Neutron Stars and Their Environments*, IAU Symposium, Vol. 218 (F. Camilo and B.M. Gaensler, eds.), 2004; S. M. Ransom, et al., Science, 307, 892, 2005. (Evidence for massive neutron stars.)

S.L. Shapiro and S.A. Teukolsky, *Black Holes, White Dwarfs and Neutron Stars.* Wiley, New York, 1983. (Comprehensive text on physics of compact stars and black holes.) (I)