

## Neutron Stars

Neutron stars are small compact stars with densities comparable to that inside nuclei,  $\rho_0 = 2.8 \times 10^{14} \text{ g cm}^{-3}$ , and radii  $R \approx 10\text{--}15 \text{ km}$ . They consist predominantly of NEUTRONS and a few percent of PROTONS and ELECTRONS. These huge neutron-rich ‘nuclei’ are bound by gravitation and require a minimum neutron star mass of  $\sim 0.1M_\odot$ . Above a maximum (Chandrasekhar) mass of order  $2\text{--}3M_\odot$  neutron stars are unstable towards gravitational collapse to BLACK HOLES.

Neutron stars are formed in type II or Ib SUPERNOVA explosions when massive stars ( $M \geq 10M_\odot$ ) run out of nuclear fuel after burning for millions of years. When the iron core in the center of the aging stars exceeds its Chandrasekhar mass,  $\sim 1.5M_\odot$ , the star undergoes gravitational collapse in just seconds and suffers violent death. Gravitational and kinetic energy of the order  $\sim 10^{53}$  ergs is released mainly by neutrino emission that blows off the outer layers. Only  $\sim 1\%$  of the energy is actually seen in a brilliant burst, the supernova. Measurements of isotopic abundances of various elements ( $r$ - and  $s$ -processes) give some insight into the densities and temperatures during certain stages of the explosion in which all heavier elements in the universe were made. Supernova explosions occur at a rate of one to three per century in our Galaxy. Historically, the Crab supernova was first recorded by the Chinese in AD 1054, and could be seen in daylight. The discovery in 1967 of a rotating neutron star (a radio pulsar) in the CRAB NEBULA supernova remnant confirmed the 1933 hypothesis of Baade and Zwicky, formulated a year after Chadwick discovered the neutron, that neutron stars are formed in supernova explosions. In our Galaxy astrophysicists expect a large abundance,  $\sim 10^8$ , of neutron stars but they only manifest themselves if powered by rotation, accretion, nuclear power or residual heat.

Radio PULSARS were first discovered by Bell and Hewish in 1967 and extensive searches have led to  $\sim 1200$  known pulsars at present. Pulsars are rotation powered neutron stars where the magnetic  $B$  and rotational  $\Omega$  axes

are misaligned by an angle  $\theta$ . Consequently they emit dipole radiation in the form of radio waves that appear to pulse on and off like a lighthouse beacon as the pulsar beam sweeps across the Earth with the spin frequency of the neutron star. The rotational energy loss for dipole radiation is

$$\dot{E} = I\Omega\dot{\Omega} = -\frac{B^2 R^6 \Omega^4 \sin^2 \theta}{6c^3} \quad (1)$$

where the moment of inertia for a typical neutron star is  $I \sim 10^{45} \text{ g cm}^2$ . The radio pulses are extremely regular with periods in the range  $1.5 \text{ ms} \leq P \leq 8.5 \text{ s}$  and the pulsars are spinning down slowly with period derivatives of the order  $\dot{P} \sim 10^{-12}\text{--}10^{-21}$ . The pulsar age is from equation (1) given by  $t \approx P/2\dot{P}$  and the magnetic field  $B \sim 10^{12} \text{ G} (\dot{P} \times 10^{15} \text{ P s}^{-1})^{1/2}$ . The resulting magnetic fields of the order of  $B \approx 10^{12} \text{ G}$  are independently confirmed by cyclotron absorption lines found in x-ray spectra. Most pulsars are old ( $\sim 10$  million years) and slowly rotating with relatively small period derivatives. In a ( $P$ ,  $\dot{P}$ ) diagram they cluster around  $P \approx 1 \text{ s}$  and  $\dot{P} \approx 10^{-15}$ . A few young pulsars, e.g. those such as the CRAB and VELA PULSARS, have short periods and large period derivatives.

The nearest known neutron star, RXJ185635-3754, located in the southern constellation Corona Australis, was imaged by the Hubble Space Telescope in 2001. Its distance is estimated by parallax at only 200 light years. From its black body spectrum, a surface temperature of half a million Kelvin is found, and from its flux a radius of order 10 km is inferred. Circumstantial evidence indicates that it was born in a supernova explosion a million years ago. Such an age and surface temperature is compatible with standard cooling predictions.

Binary pulsars were discovered by Hulse and Taylor in 1973. They form a distinct subclass of mainly millisecond radio pulsars with periods  $1.56 \text{ ms} \leq P \leq 100 \text{ ms}$ . The period derivatives are very small corresponding to very small magnetic fields  $B \sim 10^8\text{--}10^{10} \text{ G}$ . They are believed to be old recycled pulsars, which have been spun up by mass ACCRETION. In this process the magnetic fields of the pulsars have decayed. After the recycling the spun-up millisecond pulsars are expected to emit radio waves for billions of years. About 30—more than half of the known millisecond pulsars—are found in BINARY STARS where the companion is either a WHITE DWARF or a neutron star. Six double neutron stars are known so far. By measuring the inward spiralling or orbital decay one can determine many parameters in the binary systems such as the neutron star and companion masses, orbital periods and period derivatives, orbital distances and inclination. Parameters are overdetermined and provide a test of general

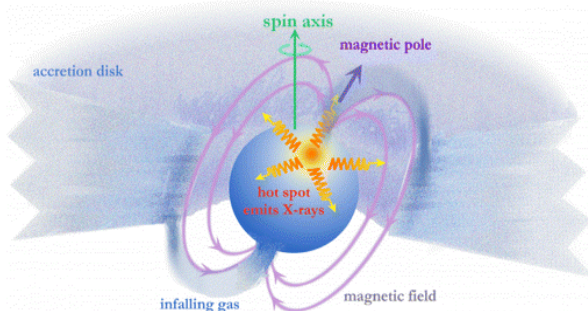
**Table 1.** Properties of a typical neutron star.

Mass	$M$	$\sim 1.4M_\odot$
Radius	$R$	10–15 km
Central densities	$\rho_c$	$\sim 10^{15} \text{ g cm}^{-3}$
Moment of inertia	$I$	$\sim 10^{45} \text{ g cm}^{-2}$
Rotation period	$P$	0.0015–8.5 s
Spin down	$\dot{P}$	$\sim 10^{-15}$
Magnetic fields	$B$	$\sim 10^{12} \text{ G}$
Temperatures	$T$	$\lesssim 5 \times 10^6 \text{ K}$

relativity to an unprecedented accuracy. The PERIASTRON advance in PSR 1913 + 16 is  $4.2^\circ$  per year as compared with 43 arcseconds per century for Mercury, which was originally used by Einstein to test his theory of general relativity. Binary neutron stars all have masses in the narrow range  $1.35 \pm 0.07 M_\odot$ . This number is suspiciously close to the Chandrasekhar mass of the iron core,  $M_{ch} \simeq 1.5 M_\odot$ , when subtracting the gravitational energy loss,  $\sim GM^2/R \sim 0.1 M$ , that disappears by neutrino emission in the collapse.

X-ray pulsars and X-RAY BURSTERS are accretion powered neutron stars (see figure 1). Almost 200 have been discovered within the last three decades by satellite borne x-ray detectors. The orbital period has been determined for about 60 of these X-RAY BINARIES. The x-ray pulsars and bursters are believed to be neutron stars accreting from high-mass ( $M \gtrsim 10 M_\odot$ ) and low mass ( $M \lesssim 1.2 M_\odot$ ) companions respectively. The former systems are fed by wind accretion whereas the latter are the result of ROCHE-LOBE overflow from a giant companion star. The x-ray pulses are most probably due to strong accretion on the magnetic poles emitting x-rays (as northern lights) with orbital frequency. The x-ray bursts are due to slow accretion spreading all over the neutron star surface before igniting in a thermonuclear flash. The resulting burst time-scales depend on accretion rates rather than orbital periods. One bursting pulsar has recently been discovered. The radiation from x-ray bursters is not blackbody and therefore only upper limits on temperatures can be extracted from observed luminosities in most cases. Masses are less accurately measured than for binary pulsars but a few, for example, the x-ray pulsars Vela X-1 ( $M \simeq (1.9 \pm 0.2) M_\odot$ ) and the x-ray burster Cygnus X-2, seem to be heavier than the binary pulsars which could be due to accretion.

Recently, a subclass of half a dozen anomalous x-ray pulsars have been discovered. They are slowly rotating,  $P \sim 10$  s, but rapidly slowing down. This requires huge magnetic fields of  $B \sim 10^{14}$  G and they have appropriately



**Figure 1.** An accreting neutron star with misaligned spin and magnetic axes.

been named ‘magnetars’. Four gamma-ray repeaters discovered so far are also slowly rotating. The anomalous x-ray pulsars, and probably also the gamma-ray repeaters, appear to reside inside SUPERNOVA REMNANTS. Together they constitute just as many galactic neutron star candidates inside supernova remnants as the radio pulsars—in spite of the extensive searches for the latter. Of the  $\sim 1200$  discovered radio pulsars only about  $\sim 10$  are associated with the 220 known supernova remnants.

Quasi-periodic oscillations (QPO) have very recently been discovered in low-mass x-ray binaries. QPOs provide a promising new method for determining masses and radii of neutron stars. The QPO are brightness oscillations in the x-ray luminosity. In many systems two kHz QPO peaks appear with frequencies that increase with accretion but with almost constant frequency difference. The pair is most likely the orbital frequency of accreting matter in Keplerian orbits around the neutron star and its beat frequency with the neutron star spin. In the case of 4U 1820-30 the accretion may have been tracked to its innermost stable orbit, since the QPO frequency displays a distinct saturation with accretion rate. From the corresponding maximum frequency  $\nu_{\text{QPO}} = 1060$  Hz, one deduces a neutron star mass of  $M \simeq 2.25 M_\odot$ . The existence of such heavy neutron stars would restrict the equation of state for neutron star matter severely.

X-ray bursts are thermonuclear explosions of accreted matter on the surface of neutron stars. After accumulating hydrogen on the surface for hours, the pressure and temperature become sufficient to trigger a runaway thermonuclear explosion seen as an x-ray burst. The energy involved is of the order of typical nuclear binding energies,  $\sim 7$  MeV per hydrogen atom. Slow accretion from a small mass companion generates a continuous background of x-rays. Each nucleon radiates its gravitational energy of  $\sim m_n GM/R \simeq 200$  MeV. The burst energy is therefore only about a per cent of the time integrated background but is released in only a few seconds. In the case of 4U 1728-34 x-ray modulation due to the neutron star spin frequency of 364 Hz has been found. It decreases, however, to 362 Hz during the first 1–2 s of the burst. A simple explanation is that the thermonuclear explosion elevates the surface of the neutron star. Conserving angular momentum,  $L \propto MR^2\nu$ , leads to a decrease in rotation by  $\Delta\nu/\nu \simeq -2\Delta R/R$ . With a frequency change of  $\Delta\nu \sim -2$  Hz and typical neutron star radius of order  $R \sim 10$  km, an elevation of order  $\Delta R \sim 20$  m is found, which is roughly in agreement with expectations but much less than on Earth due to the much stronger gravitational fields on neutron stars.

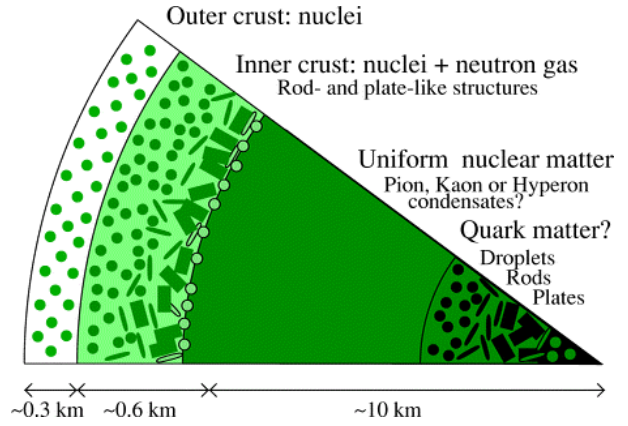
The structure of a typical  $1.4 M_\odot$  mass neutron star is to first approximation a  $\sim 1$  km thick crust and a nuclear liquid in the interior. At terrestrial densities the ground state of matter consists of  $^{56}\text{Fe}$  nuclei in a solid body-

centered cubic lattice and electrons. With increasing density, the atomic cores begin to overlap and matter becomes pressure ionized. At a density  $\sim 10^6$  times terrestrial density, or of order  $10^6 \text{ g cm}^{-3}$ , electrons become relativistic. At a density of about  $10^7 \text{ g cm}^{-3}$  it becomes energetically favorable to reduce the number of electrons by electron capture, converting protons to neutrons and form  $^{62}\text{Ni}$ . At higher densities, the equilibrium nuclei become even more neutron rich, and eventually, at a density of about  $4 \times 10^{11} \text{ g cm}^{-3}$ , all bound neutron levels in nuclei are occupied, and neutrons ‘drip’. The inner crust consists of neutron-rich nuclei embedded in a gas of neutrons and relativistic electrons. As densities approach the density of nuclear matter the nuclei may merge into intricate rod-, plate- and bubble-like structures. The sizes of the structures are determined by a competition between Coulomb and surface energies. The inner crust terminates at a density close to nuclear matter density at  $\rho \simeq 2 \times 10^{14} \text{ g cm}^{-3}$ , where the transition to a spatially uniform state occurs which is believed to be a superfluid (see figure 2).

In the core of neutron stars many other problems arise. The basic difficulty in predicting neutron star properties is that matter at supernuclear densities is not well understood. There are a number of possible states for matter. The simplest is a uniform liquid of neutrons and protons in  $\beta$ -equilibrium, with a neutralizing background of negative charge from electrons, and, when the electron chemical potential exceeds the muon rest mass, also muons. There could be other particles present, such as hyperons. Another class of possibilities is Bose condensation of mesons, either pions or kaons. Yet another is quark matter, in which the nucleons are broken down into quarks. To make progress it is necessary to develop a better understanding of many aspects of physics (see e.g. PARTICLE ASTROPHYSICS). One is the basic interactions between hadrons. While two-particle interactions between nucleons are well characterized from scattering data, the corresponding interactions for strange particles are less secure. Knowledge of many-body interactions is much more rudimentary.

The equation of state (EoS) of dense matter, e.g. pressure versus energy density  $P(\epsilon)$ , can therefore only be calculated reliably up to a few times normal nuclear saturation densities by using measured nucleon–nucleon scattering data and binding energies and saturation density of nuclei. At higher densities causality provides some constraint on the EoS. Given the EoS, the structure of non-rotating neutron stars can be calculated from the Oppenheimer–Volkoff equation

$$\frac{dP}{dr} = -G \frac{(P + \epsilon)(m + 4\pi r^3 P)}{r^2(1 - 2Gm/r)} \quad (2)$$



**Figure 2.** Schematic cross section of a neutron star. Possible components are listed, and estimates of radial dimensions are drawn (not to scale).

where  $m(r) = 4\pi \int_0^r \epsilon(r')r'^2 dr'$ . Rotation was included by Hartle. The maximum (Chandrasekhar) mass is expected to be below  $\sim 2.5M_\odot$  depending on the stiffness of the nuclear EoS, but it could be lower if phase transitions take place. Observations of large neutron star masses of order  $\sim 2.3M_\odot$  would therefore restrict the equation of state (EoS) severely for dense matter.

Glitches are sudden speed-ups in the rotation rate observed in a number of younger pulsars, e.g. the Crab and Vela. Glitches occur due to quakes in solid structures such as the crust, superfluid vortices or possibly a quark matter lattice in the core. As the rotating neutron star gradually slows down and becomes less deformed, the rigid component is strained and eventually cracks/quakes and changes its structure towards being more spherical. The moment of inertia of the rigid component,  $I_c$ , decreases abruptly and its rotation and pulsar frequency increase due to angular momentum conservation resulting in a glitch,  $\Delta\Omega/\Omega \sim 10^{-6}$ – $10^{-8}$ , which slowly relaxes on a time scale of days as the rigid and fluid components approach a common rotational frequency.

Surface temperatures may provide information about the interiors and thermal evolution of neutron stars. In recent years much effort has been devoted to measuring neutron star temperatures, especially with the Einstein Observatory and ROSAT. Neutron stars are born with interior temperatures of the order of  $10^{12} \text{ K}$ , but cool rapidly via neutrino emission to temperatures of the order of  $10^{10} \text{ K}$  within minutes and  $\lesssim 10^6 \text{ K}$  in  $10^5 \text{ yr}$ . The only information on neutron star temperatures stems from surface temperatures observed in x-ray or UV bands. Most observations are for pulsars, and it is unclear how much of the observed radiation is due to pulsar phenomena, to a synchrotron-emitting nebula or to the neutron star itself. Surface temperatures of neutron stars have been measured in a few cases or upper limits have

been set. These seem to be compatible with predictions from standard modified URCA cooling processes. Non-rotating and non-accreting neutron stars are virtually undetectable but the Hubble Space Telescope has observed one single thermally radiating neutron star RX J185635-3754. Its surface temperature is  $T \simeq 6 \times 10^5$  K  $\simeq 50$  eV and its distance is less than 120 pc from Earth. Circumstantial evidence indicates a distance of  $\sim 80$  pc which leads to a neutron star radius of 12–13 km in good agreement with modern EoS.

Gamma ray bursters (GRB) have recently been associated with afterglows from which very high REDSHIFTS ( $z \geq 1$ ) could be determined. An enormous energy output of  $E \sim 10^{53}$  ergs can be inferred, if isotropically emitted, but there is evidence for beaming or jets and the GRB therefore ‘only’ requires a total energy of  $E \sim 10^{51}$  ergs in gamma rays. Candidates for such violent events include neutron star mergers or, as indicated by recent observations of coinciding supernovae, a special class of type Ic supernova (hypernovae) where cores collapse to black holes.

NEUTRINO and GRAVITATIONAL WAVE detectors on Earth will look into the formation and cores of neutron stars. LIGO will be able to detect gravitational waves from core collapse in supernova and coalescence of binary neutron stars. Neutrinos carry away  $\sim 99\%$  of the energy in supernova explosions and their abundance, timing and spectra reveal detailed information about the explosion and the proto-neutron star. Nineteen neutrinos were detected from SN-1987A in the Large Magellanic Cloud. Modern neutrino detectors should catch several thousand neutrinos from future supernovae in our galaxy or the neighboring Magellanic Clouds.

The future of neutron stars looks bright as new windows are about to open. A new fleet of x- and gamma-ray satellites will be launched. With upgraded ground-based observatories and detectors new classes of neutron stars will be discovered and our understanding of neutron star properties will be improved.

### *Bibliography*

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