15 Compact Stars

In astrophysics those stars in which the density of matter is much larger than in ordinary stars are known as compact objects. These include white dwarfs, neutron stars, and black holes. In addition to a very high density, the compact objects are characterised by the fact that nuclear reactions have completely ceased in their interiors. Consequently they cannot support themselves against gravity by thermal gas pressure. In the white dwarfs and neutron stars, gravity is resisted by the pressure of a degenerate gas. In the black holes the force of gravity is completely dominant and compresses the stellar material to infinite density.

Compact stars in binary systems give rise to a variety of striking new phenomena. If the companion star is losing mass by a stellar wind or a Roche lobe overflow, the gas that is shed may be accreted by the compact object. This will release gravitational energy that can be observable in the form of X-ray emission and strong and rapid brightness variations.

15.1 White Dwarfs

As was mentioned in Sect. 11.2, in ordinary stars the pressure of the gas obeys the equation of state of an ideal gas. In stellar interiors the gas is fully ionised, i.e. it is plasma consisting of ions and free electrons. The partial pressures of the ions and electrons together with the radiation pressure important in hot stars comprise the total pressure balancing gravitation. When the star runs out of its nuclear fuel, the density in the interior increases, but the temperature does not change much. The electrons become degenerate, and the pressure is mainly due to the pressure of the degenerate electron gas, the pressure due to the ions and radiation being negligible. The star becomes a *white dwarf*.

As will be explained in Box 15.1 the radius of a degenerate star is inversely proportional to the cubic root of the mass. Unlike in a normal star the radius decreases as the mass increases.

The first white dwarf to be discovered was Sirius B, the companion of Sirius (Fig. 15.1). Its exceptional nature was realised in 1915, when it was discovered that its effective temperature was very high. Since it is faint, this meant that its radius had to be very small, slightly smaller than that of the Earth. The mass of Sirius B was known to be about equal to that of the Sun, so its density had to be extremely large.

The high density of Sirius B was confirmed in 1925, when the gravitational redshift of its spectral lines was measured. This measurement also provided early observational support to Einstein's general theory of relativity.

White dwarfs occur both as single stars and in binary systems. Their spectral lines are broadened by the strong gravitational field at the surface. In some white dwarfs the spectral lines are further broadened by rapid rotation. Strong magnetic fields have also been observed.

White dwarfs have no internal sources of energy, but further gravitational contraction is prevented by the pressure of the degenerate electron gas. Radiating away the remaining heat, white dwarfs will slowly cool, changing in colour from

H. Karttunen et al. (eds.), *Fundamental Astronomy*, DOI 10.1007/978-3-662-53045-0_15

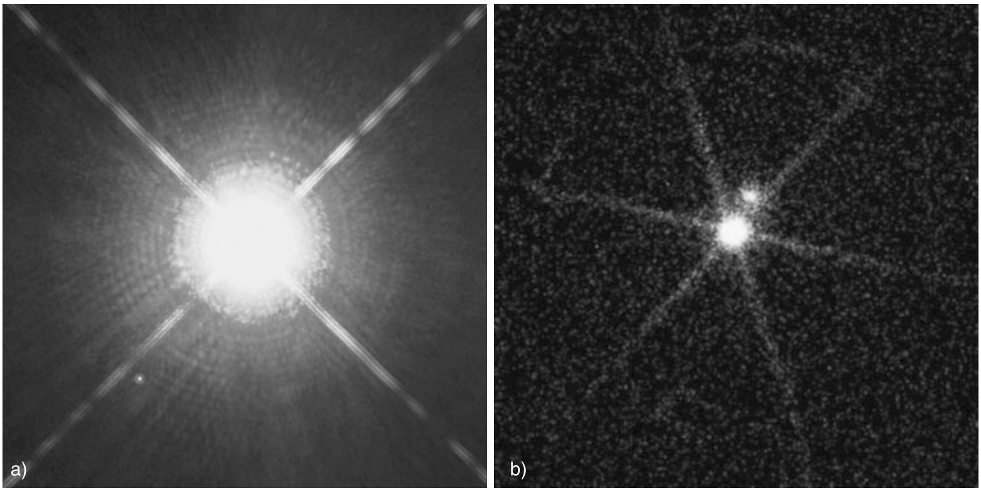

Fig. 15.1 Two views of the best-known white dwarf Sirius B, the small companion to Sirius. *On the left*, a picture in visible light by the Hubble Space Telescope. Sirius B is the tiny white dot on lower left from the overexposed image of Sirius. *On the right*, an X-ray picture of the pair taken by the Chandra X-ray observatory. Sirius B is now the brighter source, and Sirius is weaker, because its surface is much cooler than the surface of the white dwarf. (Photos NASA / HST and Chandra)

white to red and finally to black. The cooling time is comparable to the age of the Universe, and even the oldest white dwarfs should still be observable. Looking for the faintest white dwarfs has been used as a way to set a lower limit on the age of the Universe.

Cataclysmic Variables When a white dwarf is a member of a close binary system, it can accrete mass from its companion star. The most interesting case is where a main sequence star is filling its *Roche lobe*, the largest volume it can have without spilling over to the white dwarf. As the secondary evolves, it expands and begins to lose mass, which is eventually accreted by the primary. Binary stars of this kind are known as *cataclysmic variables*.

The present definition of the class of cataclysmic variables has gradually evolved, and in consequence many types of systems that were earlier viewed as separate are now collected under this heading. In principle, even type Ia supernovae should be included. The *classical novae*, whose eruptions are caused by the sudden ignition of hydrogen that has collected on the surface of the white dwarf, have been described in Sect. 14.3. In the eruptions most of the accreted gas is expelled in a shell, but if the mass transfer continues in the system further eruptions may occur, giving rise to *recurrent novae*. Finally, cataclysmic variables without eruptions, for example pre-novae or post-novae, are classified as *nova-like variables*.

The *dwarf novae*, also described in Sect. 14.3, are produced by a quite different mechanism. In their case the outbursts are not caused by thermonuclear reactions, but by instabilities in the accretion flow around the white dwarf. Although the details of the outburst mechanism are still not completely clear, the basic picture is that the disk has two possible states, a hot and a cool one, available. Under some conditions the disk cannot remain permanently in either of these states, and has to jump repeatedly between the hot outburst state and the cool quiescent state.

A special type of nova-like variables are the magnetic cataclysmic variables. In the *polars* the magnetic field is so strong that the accreted gas cannot settle into an accretion disk. Instead it is forced to follow the magnetic field lines, forming an *accretion column*. As the gas hits the surface of the white dwarf it is strongly heated giving rise to bright X-ray emission, which is a characteristic feature of polars. Systems with a slightly

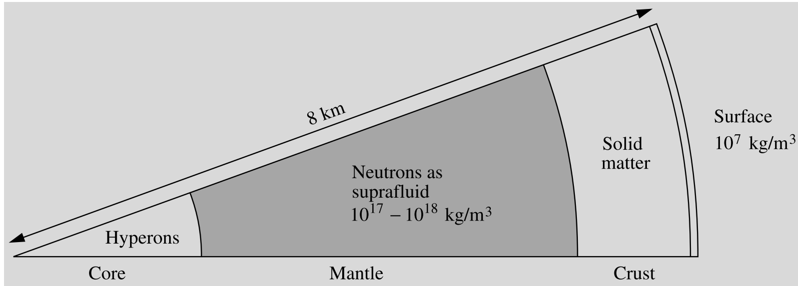

Fig. 15.2 The structure of a neutron star. The crust is rigid solid material and the mantle a freely streaming superfluid

weaker magnetic field are called *intermediate polars*. These systems exhibit both X-ray emission and variations due to an accretion disk.

15.2 Neutron Stars

If the mass of a star is large enough, the density of matter may grow even larger than in normal white dwarfs. The equation of state of a classical degenerate electron gas then has to be replaced with the corresponding relativistic formula. In this case decreasing the radius of the star no longer helps in resisting the gravitational attraction. Equilibrium is possible only for one particular value of the mass, the Chandrasekhar mass M_{Ch}, already introduced in Sect. 12.5. The value of M_{Ch} is about $1.4\,M_\odot$, which is thus the upper limit to the mass of a white dwarf. If the mass of the star is larger than M_{Ch}, gravity overwhelms the pressure and the star will rapidly contract towards higher densities. The final stable state reached after this collapse will be a *neutron star* (Fig. 15.2). On the other hand, if the mass is smaller than M_{Ch}, the pressure dominates. The star will then expand until the density is small enough to allow an equilibrium state with a less relativistic equation of state.

When a massive star reaches the end of its evolution and explodes as a supernova, the simultaneous collapse of its core will not necessarily stop at the density of a white dwarf. If the mass of the collapsing core is larger than the Chandrasekhar mass ($\gtrsim 1.4\,M_\odot$), the collapse continues to a neutron star.

An important particle reaction during the final stages of stellar evolution is the *URCA process*, which was put forward by *Schönberg* and *Gamow* in the 1940's and which produces a large neutrino emission without otherwise affecting the composition of matter. (The URCA process was invented in Rio de Janeiro and named after a local casino. Apparently money disappeared at URCA just as energy disappeared from stellar interiors in the form of neutrinos. It is claimed that the casino was closed by the authorities when this similarity became known.) The URCA process consists of the reactions

$$(Z, A) + \mathrm{e}^- \to (Z-1, A) + \nu_\mathrm{e},$$
$$(Z-1, A) \to (Z, A) + \mathrm{e}^- + \bar{\nu}_\mathrm{e},$$

where Z is the number of protons in a nucleus; A the mass number; e^- an electron; and ν_e and $\bar{\nu}_\mathrm{e}$ the electron neutrino and antineutrino. When the electron gas is degenerate, the latter reaction is suppressed by the Pauli exclusion principle. In consequence the protons in the nuclei are transformed into neutrons. As the number of neutrons in the nuclei grows, their binding energies decrease. At densities of about 4×10^{14} kg/m^3 the neutrons begin to leak out of the nucleus, and at 10^{17} kg/m^3 the nuclei disappear altogether. Matter then consists of a neutron "porridge", mixed with about 0.5 % electrons and protons.

Neutron stars are supported against gravity by the pressure of the degenerate neutron gas, just as white dwarfs are supported by electron pressure. The equation of state is the same, except that the electron mass is replaced by the neutron mass, and that the mean molecular weight is defined with respect to the number of free neutrons. Since the gas consists almost entirely of neutrons, the mean molecular weight is approximately one.

The typical diameters of neutron stars are about 10 km. Unlike ordinary stars they have

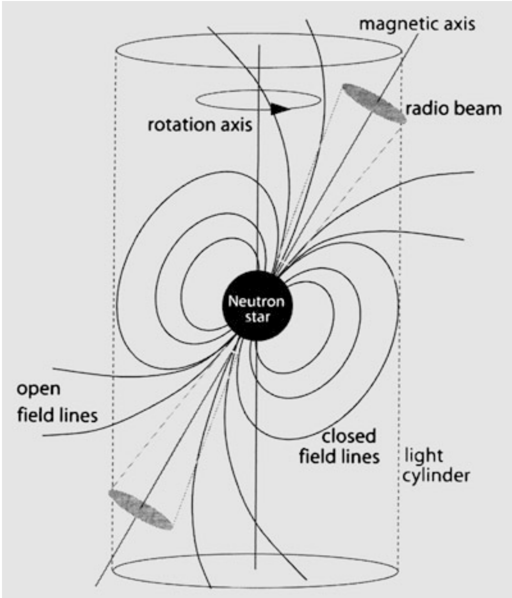

Fig. 15.3 A rotating neutron star is surrounded by a strong magnetic field which drags electrons from the surface and accelerates them to relativistic speeds over the magnetic poles. When the electrons are accelerated along the magnetic field lines, they radiate so called curvature radiation in a narrow beam. Since the magnetic axis is misaligned with the rotation axis, the beams sweep around the sky like in a lighthouse. (Lorimer–Kramer 2005, Handbook of Pulsar Astronomy, Cambridge University Press, p. 55)

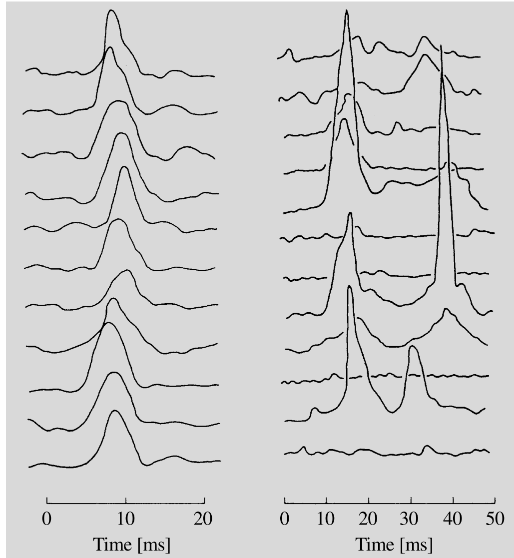

Fig. 15.4 Consecutive radio pulses at 408 MHz from two pulsars. *To the left* PSR 1642–03 and *to the right* PSR 1133+16. Observations made at Jodrell Bank. (Picture from Smith, F.G. (1977): Pulsars (Cambridge University Press, Cambridge) pp. 93, 95)

a well-defined solid surface. The atmosphere above it is a few centimetres thick. The upper crust is a metallic solid with the density growing rapidly inwards. Most of the star is a neutron superfluid, and in the centre, where the density exceeds 10^{18} kg/m^3, there may be a solid nucleus of heavier particles (hyperons), or of quark matter, where the quarks that normally constitute neutrons have become unconfined.

A neutron star formed in the explosion and collapse of a supernova will initially rotate rapidly, because its angular momentum is unchanged while its radius is much smaller than before. In a few hours the star will settle in a flattened equilibrium, rotating several hundred times per second. The initial magnetic field of the neutron star will also be compressed in the collapse, so that there will be a strong field coupling the star to the surrounding material. The angular momentum of the neutron star is steadily decreased by the emission of electromagnetic radiation, neutrinos, cosmic ray particles and possibly gravitational radiation. Thus the angular velocity decreases. The rotation can also break the star into several separate objects. They will eventually recombine when the energy of the system is reduced. In some cases the stars can remain separated, resulting e.g. in a binary neutron star.

The theory of neutron stars was developed in the 1930's, but the first observations were not made until the 1960's. At that time *the pulsars*, a new type of rapidly pulsating radio sources, were discovered and identified as neutron stars. In the 1970's neutron stars were also seen as *X-ray pulsars*, *X-ray bursters* and *magnetars*.

Pulsars The pulsars were discovered in 1967, when *Anthony Hewish* and *Jocelyn Bell* in Cambridge, England, detected sharp, regular radio pulses coming from the sky. Since then about 1500 pulsars have been discovered (Fig. 15.4). Their periods range from 0.0016 s (for the pulsar 1937 + 214) up to 20 minutes.

In addition to the steady slowing down of the rotation, sometimes small sudden jumps in the

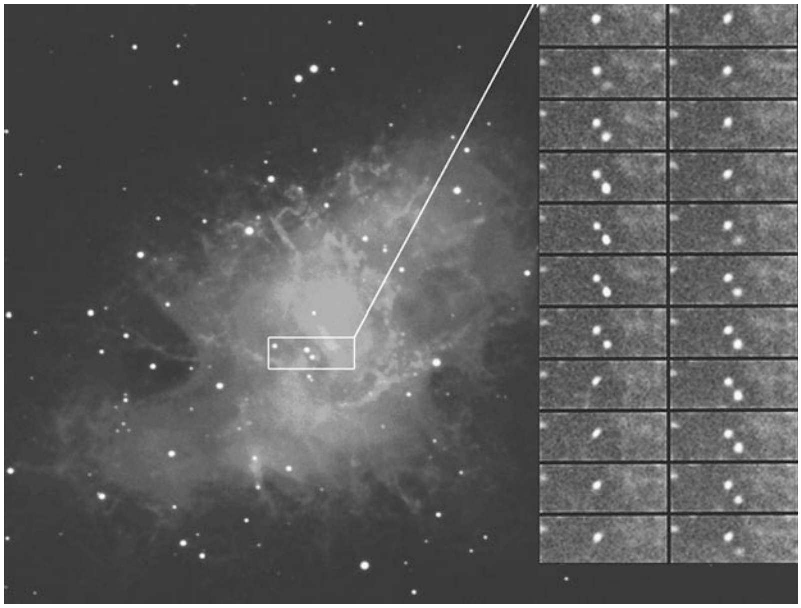

Fig. 15.5 A time-sequence of the pulsation of the Crab pulsar in visible light. The pictures were taken once about every millisecond; the period of the pulsar is about 33 milliseconds. (Photos N.A. Sharp/NOAO/AURA/NSF)

period are observed. These might be a sign of rapid mass movements in the neutron star crust ("starquakes") or in its surroundings.

The origin of the radio pulses can be understood if the magnetic field is tilted at an angle of 45°–90° with respect to the rotation axis. The field is so strong that it drags electrons from the surface and accelerates them to relativistic speeds over the magnetic poles. When the electrons are accelerated along the magnetic field lines, they radiate so called curvature radiation which is related to synchrotron radiation (Fig. 15.3). In the direction of the magnetic poles two thin beams of radio radiation are emitted. The beams sweep around the sky, and if the Earth happens to be in the path of the beam a pulsar is seen.

The best-known pulsar is located in the Crab nebula (Figs. 15.5 and 15.7). This small nebula in the constellation Taurus was noted by the French astronomer *Charles Messier* in the middle of the 18th century and became the first object in the Messier catalogue, M1. The Crab nebula was found to be a strong radio source in 1948 and an X-ray source in 1964. The pulsar was discovered in 1968. In the following year it was observed optically and was also found to be an X-ray emitter.

Neutron stars are difficult to study optically, since their luminosity in the visible region is very small (typically about $10^{-6}\,L_\odot$). For instance the Vela pulsar has been observed at a visual magnitude of about 25. In the radio region, it is a very strong pulsating source.

A few pulsars have been discovered in binary systems; the first one, PSR 1913+16, in 1974. In 1993 *Joseph Taylor* and *Russell Hulse* were awarded the Nobel prize for the detection and studies of this pulsar. The pulsar orbits about a companion, presumably another neutron star, with the orbital eccentricity 0.6 and the period 8 hours. The observed period of the pulses is altered by the Doppler effect, and this allows one to determine the velocity curve of the pulsar. These observations can be made very accurately, and it has therefore been possible to follow the changes in the orbital elements of the system over a period of several years. For example, the periastron direction of the binary pulsar has been found to rotate about 4° per year. This phenomenon can be explained by means of the general theory of relativity; in the solar system, the corresponding rotation (the minor fraction of the rotation not explained by the Newtonian mechanics) of the perihelion of Mercury is 43 arc seconds per century.

The binary pulsar PSR 1913+16 has also provided the first strong evidence for the existence of gravitational waves. During the time of observation the orbital period of the system has steadily decreased. This shows that the system is losing orbital energy at a rate that agrees exactly with that predicted by the general theory of relativity. The lost energy is radiated as gravitational waves.

Magnetars The energy emitted by common pulsars has its origin in the slowing down of their rotation. In some neutron stars, the magnetars, the magnetic field is so strong that the energy released in the decay of the field is the main source of energy. Whereas in ordinary pulsars the magnetic field is typically 10^9 T, in magnetars a typical value may be 10^9–10^{11} T.

Magnetars were first invoked as an explanation of the soft gamma repeaters (SGR), X-ray stars that irregularly emit bright, short (0.1 s) repeating flashes of low-energy gamma rays. Later a second class of mysterious objects, the anomalous X-ray pulsars (AXP), were identified as magnetars. AXP are slowly rotating pulsars, with a rotation period of 6 to 12 seconds. Despite this they are bright X-ray sources, which can be understood if their energy is of magnetic origin.

It is thought that magnetars are the remnants of stars that were more massive and rapidly rotating than those giving rise to ordinary pulsars, although the details are still subject to debate. A magnetar first appears as a SGR. During this phase, which only lasts about 10,000 years, the very strong magnetic field is slowing down the rate of rotation. At the same time the field is drifting with respect to the neutron star crust. This causes shifts in the crust structure, leading to powerful magnetic flares and the observed outbursts. After about 10,000 years the rotation has slowed down so much that the outbursts cease, leaving the neutron star observable as an AXP.

Gamma Ray Bursts For a long time the *gamma ray bursts* (GRB), very short and sharp gamma ray pulses first discovered in 1973, remained a mystery. Unlike the much less common SGR, the GRB never recurred, and they had no optical or X-ray counterparts. A first major advance was made when satellite observations with the Compton Gamma Ray Observatory showed

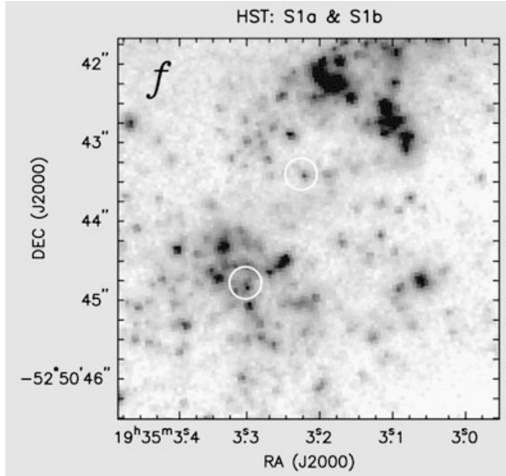

Fig. 15.6 The location of the peculiar type Ibc supernova SN 1998bw at redshift $z = 0.0085$ is in *the circle to the lower left*. This was also the position of the faint gamma-ray burst GRB 980425, the first GRB to be connected with a supernova. *The circle on the upper right* marks an ultraluminous X-ray source. (C. Kouveliotou et al. 2004, ApJ 608, 872, Fig. 1)

that the gamma ray bursts are almost uniformly distributed in the sky, unlike the known neutron stars.

The nature of the gamma ray bursts is now becoming clear thanks to dedicated observing programmes that have used burst detections by gamma and X-ray satellites such as Beppo-SAX and, in particular, Swift rapidly to look for afterglows of the GRB at optical wavelengths. The detection of these afterglows has made it possible to determine distances to the bursts and their location in their host galaxies (see Fig. 15.6).

It has become clear that there are at least two kinds of bursts, with the self-descriptive names long soft bursts, and short hard bursts. The long soft gamma ray bursts, lasting longer than 2 seconds, have now been convincingly shown to be produced in the explosions of massive stars at the end of their life, specifically supernovae of types Ib and Ic (Sect. 14.3). Only a small fraction of all type Ibc supernovae give rise to a GRB. The explosions that produce GRB have been called hypernovae, and are among the brightest objects in the Universe. A gamma ray burst observed in late 2005 took place when the Universe was only 900 million years old, making it one of the most

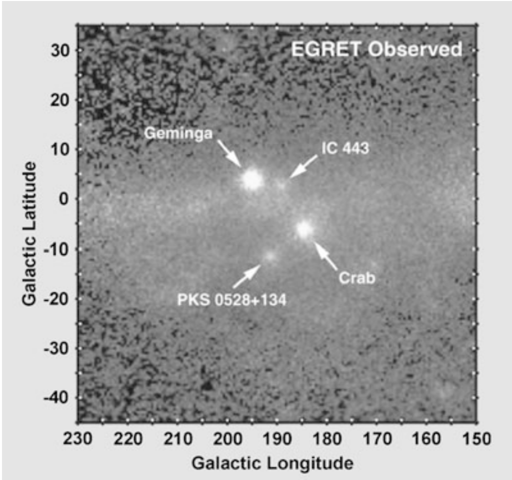

Fig. 15.7 Some pulsars shine brightly in gamma-rays. *In the center* the Crab pulsar and *on the upper left* the gamma source Geminga, which was identified in 1992 to be the nearest pulsar with a distance of about 100 pc from the Sun. (Photo by Compton Gamma Ray Observatory)

distant objects ever observed. The conditions required for hypernova explosions are still not certain.

The nature of the systems giving rise to short gamma ray bursts, lasting less than 2 seconds, have been more difficult to ascertain. The most popular theory has been that they are produced in compact binary systems consisting of two neutron stars or a neutron star and a black hole. These systems lose energy by gravitational radiation, and eventually the two components should merge, producing a burst of gamma radiation. This theory has now received strong support when the afterglow of a few short bursts has been detected in the outer parts of their host galaxies. Since the stars in these regions are all old and no longer give rise to core-collapse supernovae, the neutron star merger hypothesis appears most likely. However, it is still also possible that some of the short bursts are exceptionally bright magnetar flares.

Box 15.1 (The Radius of White Dwarfs and Neutron Stars) The mass of a white dwarf or a neutron star determines its radius. This follows from the equation of hydrostatic equilibrium and from the pressure-density relation for a degenerate gas. Using the hydrostatic equilibrium equation (11.1)

$$\frac{\mathrm{d}P}{\mathrm{d}r} = -\frac{GM_r\rho}{r^2}$$

one can estimate the average pressure P:

$$\left|\frac{\mathrm{d}P}{\mathrm{d}r}\right| \approx \frac{P}{R} \propto \frac{M \times M/R^3}{R^2} = \frac{M^2}{R^5}.$$

Here we have used $\rho \propto M/R^3$. Thus the pressure obeys

$$P \propto M^2/R^4. \tag{1}$$

In the nonrelativistic case, the pressure of a degenerate electron gas is given by (11.16):

$$P \approx \left(h^2/m_\mathrm{e}\right)(\mu_\mathrm{e} m_\mathrm{H})^{-5/3}\rho^{5/3}$$

and hence

$$P \propto \frac{\rho^{5/3}}{m_\mathrm{e}\mu_\mathrm{e}^{5/3}}. \tag{2}$$

By combining (1) and (2) we obtain

$$\frac{M^2}{R^4} \propto \frac{M^{5/3}}{R^5 m_\mathrm{e}\mu_\mathrm{e}^{5/3}}$$

or

$$R \propto \frac{1}{M^{1/3} m_\mathrm{e}\mu_\mathrm{e}^{5/3}} \propto M^{-1/3}.$$

Thus the smaller the radius of a white dwarf is, the larger its mass will be. If the density becomes so large that the relativistic equation of state (11.17) has to be used, the expression for the pressure is

$$P \propto \rho^{4/3} \propto \frac{M^{4/3}}{R^4}.$$

As the star contracts, the pressure grows at the same rate as demanded by the condition for hydrostatic support (1). Once contraction has begun, it can only stop when the state of matter changes: the electrons and protons combine into neutrons. Only a star that is massive enough can give rise to a relativistic degenerate pressure.

The neutrons are fermions, just like the electrons. They obey the Pauli exclusion principle, and the degenerate neutron gas pressure is obtained from an expression analogous to (2):

$$P_n \propto \frac{\rho^{5/3}}{m_n \mu_n^{5/3}},$$

where m_n is the neutron mass and μ_n, the molecular weight per free neutron. Correspondingly, the radius of a neutron star is given by

$$R_{ns} \propto \frac{1}{M^{1/3} m_n \mu_n^{5/3}}.$$

If a white dwarf consists purely of helium, $\mu_e = 2$; for a neutron star, $\mu_n \approx 1$. If a white dwarf and a neutron star have the same mass, the ratio of their radii is

$$\frac{R_{wd}}{R_{ns}} = \left(\frac{M_{ns}}{M_{wd}}\right)^{1/3} \left(\frac{\mu_n}{\mu_e}\right)^{5/3} \frac{m_n}{m_e}$$
$$\approx 1 \times \left(\frac{1}{2}\right)^{5/3} \times 1840 \approx 600.$$

Thus the radius of a neutron star is about 1/600 of that of a white dwarf. Typically R_{ns} is about 10 km.

15.3 Black Holes

If the mass of a star exceeds M_{OV} (Sect. 12.5), and if it does not lose mass during its evolution it can no longer reach any stable final state. The force of gravity will dominate over all other forces, and the star will collapse to a black hole. A black hole is black because not even light can escape from it. Already at the end of the 18th century *Laplace* showed that a sufficiently massive body would prevent the escape of light from its surface. According to classical mechanics, the escape velocity from a body of radius R and mass M is

$$v_e = \sqrt{\frac{2GM}{R}}.$$

This is greater than the speed of light, if the radius is smaller than the critical radius

$$R_S = 2GM/c^2. \qquad (15.1)$$

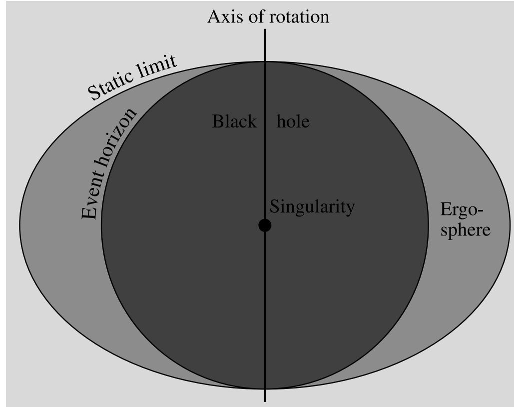

Fig. 15.8 A black hole is surrounded by a spherical event horizon. In addition to this a rotating black hole is surrounded by a flattened surface inside which no matter can remain stationary. This region is called the ergosphere

The same value for the critical radius, the *Schwarzschild radius*, is obtained from the general theory of relativity. For example, for the Sun, R_S is about 3 km; however, the Sun's mass is so small that it cannot become a black hole by normal stellar evolution. Because the mass of a black hole formed by stellar collapse has to be larger than M_{OV} the radius of the smallest black holes formed in this way is about 5–10 km.

The properties of black holes have to be studied on the basis of the general theory of relativity, which is beyond the scope of this book. Thus only some basic properties are discussed qualitatively.

An *event horizon* is a surface through which no information can be sent out, even in principle. A black hole is surrounded by an event horizon at the Schwarzschild radius (Fig. 15.8). In the theory of relativity each observer carries with him his own local measure of time. If two observers are at rest with respect to each other at the same point their clocks go at the same rate. Otherwise their clock rates are different, and the apparent course of events differs, too.

Near the event horizon the different time definitions become significant. An observer falling into a black hole reaches the centre in a finite time, according to his own clock, and does not notice anything special as he passes through the event horizon. However, to a distant observer he never seems to reach the event horizon; his velocity of fall seems to decrease towards zero as he approaches the horizon.

The slowing down of time also appears as a decrease in the frequency of light signals. The formula for the gravitational redshift can be written in terms of the Schwarzschild radius as (Appendix B)

$$\nu_\infty = \nu\sqrt{1-\frac{2GM}{rc^2}} = \nu\sqrt{1-\frac{R_S}{r}}. \qquad (15.2)$$

Here, ν is the frequency of radiation emitted at a distance r from the black hole and ν_∞ the frequency observed by an infinitely distant observer. It can be seen that the frequency at infinity approaches zero for radiation emitted near the event horizon.

Since the gravitational force is directed towards the centre of the hole and depends on the distance, different parts of a falling body feel a gravitational pull that is different in magnitude and direction. The tidal forces become extremely large near a black hole so that any material falling into the hole will be torn apart. All atoms and elementary particles are destroyed near the central point, and the final state of matter is unknown to present-day physics. The observable properties of a black hole do not depend on how it was made.

Not only all information on the material composition disappears as a star collapses into a black hole; any magnetic field, for example, also disappears behind the event horizon. A black hole can only have three observable properties: mass, angular momentum and electric charge.

It is improbable that a black hole could have a significant net charge. An electrically charged black hole would attract particles with opposite charge until it became neutral. Rotation, on the other hand, is typical to stars, and thus black holes, too, must rotate. Since the angular momentum is conserved, stars collapsed to black holes must rotate very fast.

In 1963 *Roy Kerr* managed to find a solution of the field equations for a rotating black hole. In addition to the event horizon a rotating hole has another limiting surface, an ellipsoidal *static limit* (Fig. 15.8). Objects inside the static limit cannot be kept stationary by any force, but they must orbit the hole. However, it is possible to escape from the region between the static limit and the event horizon, called the *ergosphere*. In fact it is possible to utilise the rotational energy of a black hole by dropping an object to the ergosphere in such a way that part of the object falls into the hole and another part is slung out. The outcoming part may then have considerably more kinetic energy than the original object.

At present the only known way in which a black hole could be directly observed is by means of the radiation from gas falling into it. For example, if a black hole is part of a binary system, gas streaming from the companion will settle into a disk around the hole. Matter at the inner edge of the disk will fall into the hole. The accreting gas will lose a considerable part of its energy (up to 40 % of the rest mass) as radiation, which should be observable in the X-ray region.

Some rapidly and irregularly varying X-ray sources of the right kind have been discovered. The first strong evidence for black hole in an X-ray binary was for Cygnus X-1 (Fig. 15.9). Its luminosity varies on the time scale of 0.001 s, which means that the emitting region must be only 0.001 light-seconds or a few hundred kilometres in size. Only neutron stars and black holes are small and dense enough to give rise to such high-energy processes. Cygnus X-1 is the smaller component of the double system HDE 226868. The larger component is an optically visible supergiant with a mass 20–25 $M_\odot$. The mass of the unseen component has been calculated to be 10–15 $M_\odot$. If this is correct, the mass of the secondary component is much larger than the upper limit for a neutron star, and thus it has to be a black hole.

Today 20 such systems are known, where the compact component has a mass larger than 3 $M_\odot$, and therefore is probably a black hole. As shown in Fig. 15.10 these can be of very different sizes. Nearly all of them have been discovered as X-ray novae.

Many frightening stories about black holes have been invented. It should therefore be stressed that they obey the same dynamical laws as other stars—they are not lurking in the darkness of space to attack innocent passers-by. If the Sun became a black hole, the planets would continue in their orbits as if nothing had happened.

Fig. 15.9 *The arrow* shows the variable star V1357 Cyg. Its companion is the X-ray source Cygnus X-1, suspected to be a black hole. Cyg X-1 itself is so faint that it can be observed by its X-ray radiation only. The bright star to *the lower right* of V1357 is η Cygni, one of the brightest stars in the constellation Cygnus

So far we have discussed only black holes with masses in the range of stellar masses. There is however no upper limit to the mass of a black hole. Many active phenomena in the nuclei of galaxies can be explained with supermassive black holes with masses of millions or thousands of millions solar masses (see Sect. 19.7).

15.4 X-ray Binaries

Close binaries where a neutron star or a black hole is accreting matter from its companion, usually a main sequence star, will be visible as strong X-ray sources. They are generally classified as *high-mass X-ray binaries* (HMXB), when the companion has a mass larger than about $10\,M_\odot$, and *low-mass X-ray binaries* (LMXB) with a companion mass smaller than $1.2\,M_\odot$. In HMXBs the source of the accreted material is a strong stellar wind. LMXBs are produced by Roche-lobe overflow of the companion star, either because the major axis of the binary decreases due to angular momentum loss from the system, or else because the radius of the companion is increasing as it evolves.

Because of the rapid evolution of the massive component in HMXBs these systems are young and short-lived, 10^5–10^7 a. In LMXBs the lifetime is determined by the mass-transfer process, and may be longer, 10^7–10^{10} a. In many respects they are similar to cataclysmic variables, and may give rise to analogous phenomena.

Many kinds of variable X-ray sources have been discovered since they were first observed in the 1970's. Among these, the X-ray pulsars and the X-ray bursters can only be neutron stars. In other types of X-ray binaries it can be difficult to determine whether the primary is a neutron star or a black hole.

Neutron stars and black holes are formed in supernova explosions, and in a binary system the explosion would normally be expected to disrupt the binary. An X-ray binary will only form under special conditions. Some examples are shown in Sect. 12.6.

X-ray Pulsars X-ray pulsars always belong to binary systems and may be either HMXBs or LMXBs. The pulse periods of X-ray pulsars in high-mass systems are significantly longer than those of radio pulsars, from a few seconds to tens of minutes. In contrast to radio pulsars, the period of the pulsed emission of these pulsars decreases with time.

The characteristic properties of X-ray pulsars can be understood from their binary nature. A neutron star formed in a binary system is first seen as a normal radio pulsar. Initially, the strong radiation of the pulsar prevents gas from falling onto it. However, as it slows down, its energy decreases, and eventually the stellar wind from the companion can reach its surface. The incoming gas is channelled to the magnetic polar caps of the neutron star, where it emits strong X-ray radiation as it hits the surface. This produces the observed pulsed emission.

In low-mass systems, the angular momentum of the incoming gas speeds up the rotation of

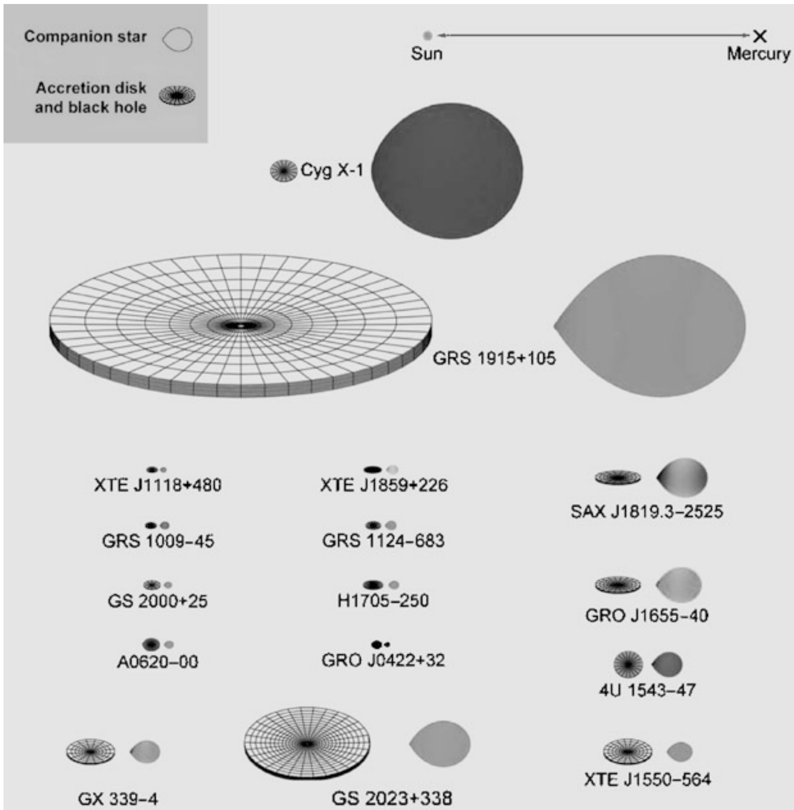

Fig. 15.10 Scale drawings of 16 black-hole binaries in the Milky Way (courtesy of J. Orosz). The Sun–Mercury distance (0.4 AU) is shown *at the top*. The estimated binary inclination is indicated by the tilt of the accretion disk. (R.A. Remillard, J.E. McClintock 2006, ARAA 44, 54)

the pulsar. The maximum possible rotation rate of a neutron star before centrifugal forces start to break it up corresponds to a period of about a millisecond. A few *millisecond pulsars* with periods of this order are known, both in the radio and in the X-ray region. It is thought that these are (or, in the radio case, have once been) members of binary systems.

The emission curve of a typical fast X-ray pulsar, Hercules X1, is shown in Fig. 15.11. The period of the pulses is 1.24 s. This neutron star is part of an eclipsing binary system, known from optical observations as HZ Herculis. The orbital properties of the system can therefore be determined. Thus e.g. the mass of the pulsar is about one solar mass, reasonable for a neutron star.

X-ray Bursters X-ray bursters are irregular variables, showing sudden brightenings, known as type I X-ray bursts, at random times (Fig. 15.12). The typical interval between outbursts is a few hours or days, but more rapid bursters are also known. The strength of the outburst seems to be related to the recharging time.

Type I X-ray bursts are analogous to the eruptions of classical novae. However, the source of radiation in X-ray bursters cannot be the ignition of hydrogen, since the maximum emission is in the X-ray region. Instead, gas from the companion settles on the surface of the neutron star, where hydrogen burns steadily to helium. Then, when the growing shell of helium reaches a critical temperature, it burns to carbon in a rapid helium flash. Since, in this case, there are no thick damping outer layers, the flash appears as a burst of X-ray radiation.

X-ray Novae The X-ray pulsars and bursters have to be neutron stars. Other X-ray binaries may be either neutron stars or black holes. All compact X-ray sources are variable to some extent. In the *persistent sources* the variations are moderate, an the sources always visible. The majority of sources are *transient*.

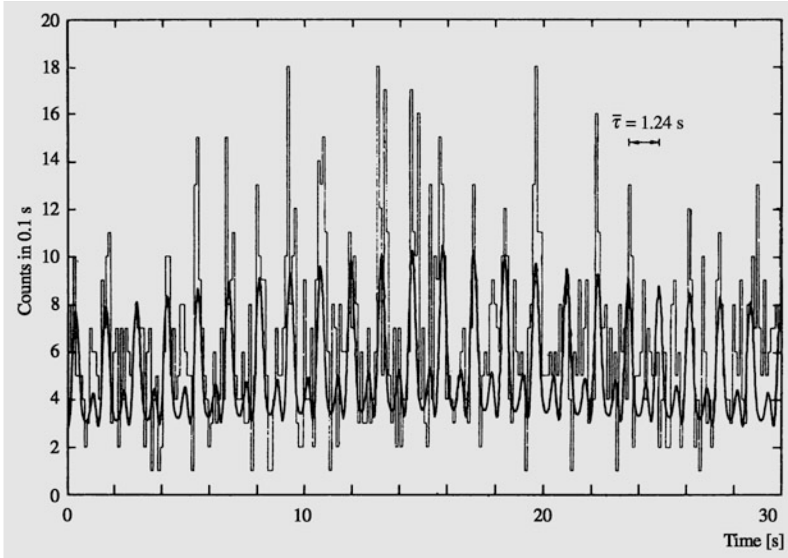

Fig. 15.11 The pulses of the X-ray pulsar Hercules X1 have the period 1.24 s. The best-fitting curve has been superimposed on the observations. (Tananbaum, H. et al. (1972): Astrophys. J. (Lett.) **174**, L143)

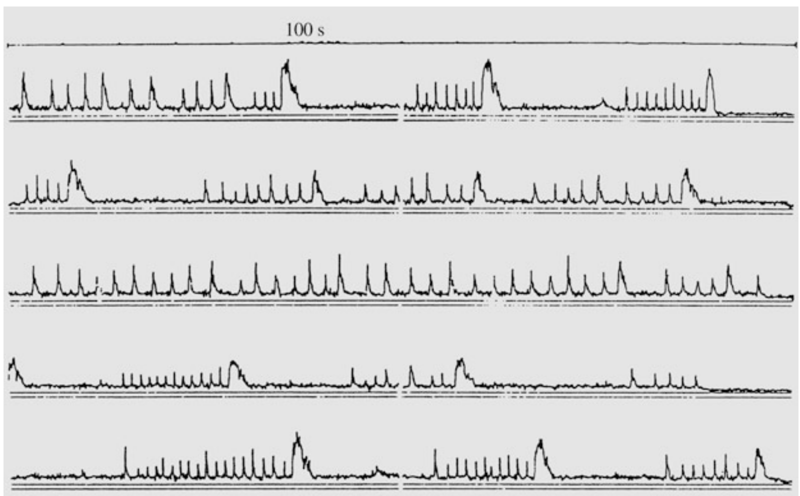

Fig. 15.12 The variations of the rapid X-ray burster MXB 1730–335. An 100 second interval is marked in the diagram. (Lewin, W.H.G. (1977): Ann. N.Y. Acad. Sci. **302**, 310)

If the X-ray bursters correspond to classical novae, the counterparts of dwarf novae are the *X-ray novae*, also known as *soft X-ray transients* (SXT). Quantitatively there are large differences between these types of systems. Dwarf novae have outbursts lasting for a few days at intervals of a few months, for SXTs the outbursts happen at decade-long intervals and last for months. A dwarf nova brightens by a factor about 100 during outbursts, a SXT by a factor of 10^6. The light-curves of neutron-star and black-hole SXTs are compared in Fig. 15.13.

The SXTs are alternating between (at least) two states: During the high state thermal radiation from the accretion disk dominates, whereas in the low state the X-ray have a higher energy, and are produced by Compton scattering by hot electrons in a disk corona or a jet.

Microquasars One interesting aspect of X-ray binaries is their connection to models of active galactic nuclei (AGN, Sect. 19.7). In both systems a black hole, which in the case of AGN may have a mass in the range 10^6–$10^{10}\,M_\odot$, is surrounded by an accretion disk.

In an X-ray binary there is similarly an accretion disk surrounding a compact object, a stellar-mass black hole. It will exhibit phenomena in many respects similar to those in AGN. Since the galactic sources are much nearer, and vary on much shorter time-scales, they may allow more detailed observations of these phenomena.

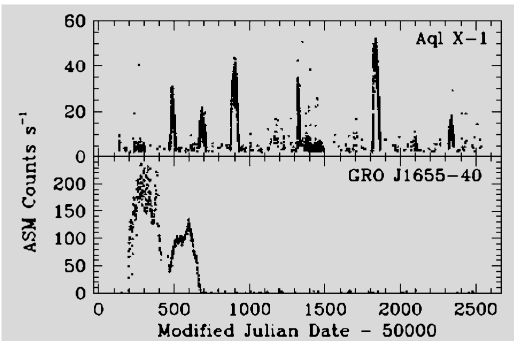

Fig. 15.13 Light-curves of a neutron-star (Aql X-1) and a black-hole (GRO J1655–40) transient source, as observed by the All Sky Monitor on RXTE. (D. Psaltis 2006, in Compact Stellar X-ray Sources, ed. Lewin, vdKlis, CUP, p. 16, Fig. 1.9)

For example, relativistic jets perpendicular to the disk are common in AGN, and they can also be expected in X-ray binaries. A few examples of such *microquasars* have been discovered, see Fig. 15.14.

Furthermore, in AGN the jet may sometimes be pointing straight at us. Relativistic effects will then lead to a brightening of the source. In a microquasar there might be a similar effect, which would provide one explanation for the *ultraluminous X-ray sources* (ULX), sources which appear to be too luminous to be produced by ordinary stellar-mass black holes. This is important, because according to an alternative model ULXs contain an *intermediate mass black hole* with a mass about $10^3\,M_\odot$. The origin of such intermediate mass black holes, if they exist, is an intriguing problem.

15.5 Examples

Example 15.1 Assume that the Sun collapses into a neutron star with a radius of 20 km. (a) What will be the mean density of the neutron star? (b) What would be it rotation period?

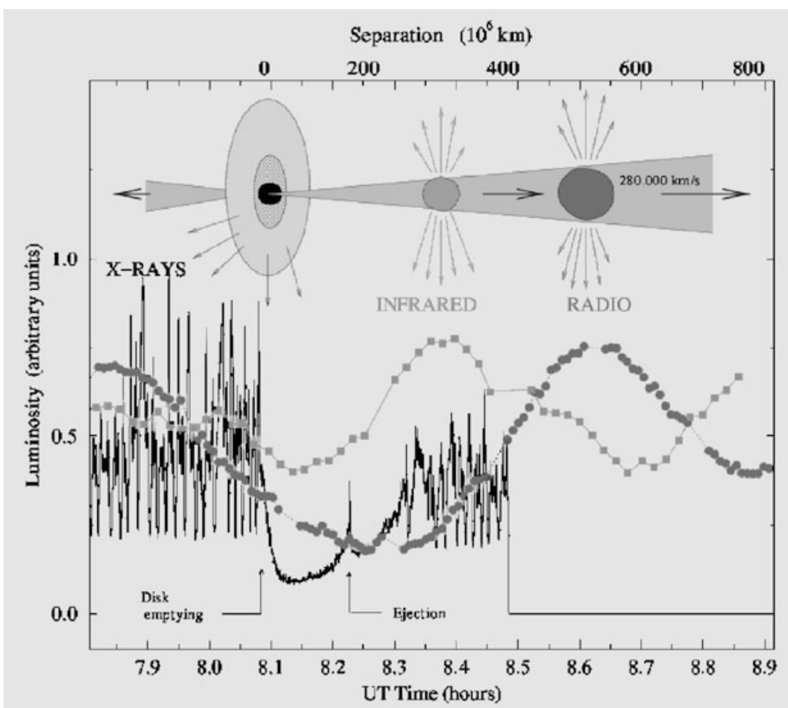

Fig. 15.14 Observed outburst of the microquasar GRS 1915+105 on 9 September, 1997. The disappearance of the internal part of the accretion disc (decrease in the X-ray flux) is followed by an ejection of relativistic plasma clouds (oscillation in the infrared and radio). (S. Chaty, astro-ph/0607668)

(a) The mean density is

$$\rho = \frac{M_\odot}{\frac{4}{3}\pi R^3} = \frac{2 \times 10^{30}\ \mathrm{kg}}{\frac{4}{3}\pi (20 \times 10^3)^3\ \mathrm{m}^3} \approx 6 \times 10^{16}\ \mathrm{kg/m}^3.$$

One cubic millimetre of this substance would weigh 60 million kilos.

(b) To obtain an exact value, we should take into account the mass distributions of the Sun and the resulting neutron star. Very rough estimates can be found assuming that both are homogeneous. Then the moment of inertia is $I = \frac{2}{5} M R^2$, and the angular momentum is $L = I\omega$. The rotation period is then obtained as in Example 12.1:

$$\begin{aligned} P &= P_\odot \left(\frac{R}{R_\odot} \right)^2 \\ &= 25\ \mathrm{d} \left(\frac{20 \times 10^3\ \mathrm{m}}{6.96 \times 10^8\ \mathrm{m}} \right)^2 = 2.064 \times 10^{-8}\ \mathrm{d} \\ &\approx 0.0018\ \mathrm{s}. \end{aligned}$$

The Sun would make over 550 revolutions per second.

Example 15.2 What should be the radius of the Sun if the escape velocity from the surface were to exceed the speed of light?

The escape velocity exceeds the speed of light if

$$\sqrt{\frac{2GM}{R}} > c$$

or

$$R < \frac{2GM}{c^2} = R_\mathrm{S}.$$

For the Sun we have

$$\begin{aligned} R_\mathrm{S} &= \frac{2 \times 6.67 \times 10^{-11}\ \mathrm{m}^3\,\mathrm{s}^{-2}\,\mathrm{kg}^{-1} \times 1.989 \times 10^{30}\ \mathrm{kg}}{(2.998 \times 10^8\ \mathrm{m\,s}^{-1})^2} \\ &= 2950\ \mathrm{m}. \end{aligned}$$

15.6 Exercises

Exercise 15.1 The mass of a pulsar is $1.5\,M_\odot$, radius 10 km, and rotation period 0.033 s. What is the angular momentum of the pulsar? Variations of 0.0003 s are observed in the period. If they are due to radial oscillations ("starquakes"), how large are these oscillations?

Exercise 15.2 In *Dragon's Egg* by Robert L. Forward a spaceship orbits a neutron star at a distance of 406 km from the centre of the star. The orbital period is the same as the rotation period of the star, 0.1993 s.

(a) Find the mass of the star and the gravitational acceleration felt by the spaceship.
(b) What is the effect of the gravitation on a 175 cm tall astronaut, if (s)he stands with her/his feet pointing towards the star? And if (s)he is lying tangential to the orbit?

Exercise 15.3 A photon leaves the surface of a star at a frequency ν_e. An infinitely distant observer finds that its frequency is ν. If the difference is due to gravitation only, the change in the energy of the photon, $h\Delta\nu$, equals the change in its potential energy. Find the relation between ν and ν_e, assuming the mass and radius of the star are M and R. How much will the solar radiation redshift on its way to the Earth?