PHY20003 ASTROPHYSICS

Lecture 20 Compact objects

20.1 Pulsars

In 1967 the first pulsar was discovered.

A pulsar is a stellar object that periodically emits pulses of electromagnetic radiation. The periods of pulsars range from ~1 ms up to a few seconds. The period of each pulsar is very stable, but the strength of the emission can vary significantly.

Figure 20.1: Rough sketch of the pulsar lighthouse model

If the source of radiation is only visible from the Earth when facing it, then the rotation period, P, can be directly determined from the frequency, f, as $P = 1/f$

Example calculation: Show that a pulsar emitting pulses of electromagnetic radiation at 1000Hz cannot be a white dwarf.

We can also estimate the density of the neutron star by assuming the pulsar is spinning near its break-up velocity

$$\frac{v^2}{R} = \frac{GM}{R^2} \tag{20.1}$$

$$v = \sqrt{\frac{GM}{R}} \tag{20.2}$$

The rotation period is given by

$$P = \frac{2\pi R}{v} \tag{20.3}$$

So that

$$P = \frac{2\pi R^{\frac{3}{2}}}{\sqrt{GM}} \tag{20.4}$$

We know that $M = \frac{4\pi}{3} R^3\rho$, so we get

$$P = \frac{2\pi R^{\frac{3}{2}}}{\sqrt{\left(\frac{4\pi G}{3}\rho R^3\right)}} \tag{20.5}$$

And, filling in the variables, we find that

$$P = \frac{3.8 \cdot 10^5}{\rho^{0.5}} \text{ sec} \tag{20.6}$$

This results in pulsar densities of ~ $10^{12} \rightarrow 10^{16}$ kg/m^3.

20.2 Black holes

Consider an object with mass M and radius R. The escape velocity from its surface is obtained by letting the kinetic energy of a body of mass m equal the gravitational potential energy

$$\frac{1}{2}mv^2 = \frac{GMm}{R} \tag{20.7}$$

Therefore

$$v_{esc} = \sqrt{\frac{2GM}{R}} \tag{20.8}$$

As $R \to 0$, $v_{esc} \to \infty$

At $v_{esc} = c$ even light can't escape from the surface, and the object becomes a black hole. The associated radius is known as the Schwartzschild Radius:

$$R_S = \frac{2GM}{c^2} \tag{20.9}$$

Using a mass in solar masses we find

$$R \simeq 3\frac{M}{M_\odot}\ \mathrm{km} \tag{20.10}$$

It is impossible to observe anything happening with this surface. This surface is known as the event horizon.

If it is impossible to observe the light escaping from a black hole, how can we detect them?

1) If the stars in a binary system are of different masses, then one will evolve of the main sequence first, becoming a WD, a pulsar or a black hole (see Lecture 17).

Such a system should be visible due to the motion of the visible companion, ad we can use the mass function

$$f(M_1, M_2) = \frac{4\pi^2}{G}\frac{r_1'^3}{P^2} = \frac{M_2^3 \sin^3 i}{(M_1 + M_2)^2} \tag{20.11}$$

To determine the lower limit on the mass of the unseen companion. If M_1 is found from the spectral type, we can obtain a lower limit to the mass of the unobserved companion.

There are several single-lined spectroscopic binary systems (i.e. spectroscopic binaries where only one of the companions can be detected directly) the show $M_2 > 3\ M_\odot$.

2) If the separation between the companions is small enough, the invisible massive object will be able to pull material from its companion when it evolves of the main sequence (often through Roche lobe overflow (see Lecture 21), or from the accretion material being blown of the companion star due to the stellar wind).

Matter falling onto the compact object (black hole or neutron star) will spiral in, forming an <u>accretion disk</u>.

Figure 20.2: A rough sketch of a black hole accreting from a binary companion

The gravitational potential energy of the material will be released as thermal energy.

If we consider a $5\ M_{\odot}$ black hole, it has a Schwarzschild radius of $R_s \simeq 15$ km. The potential energy for a mass, m, brought to this distance is given by

$$PE = -\frac{GMm}{R} \sim 4 \cdot 10^{16}\ \mathrm{J\ kg^{-1}} \tag{20.12}$$

Assuming that the black hole accretes mass from its companion at a rate of $\dot{M} \sim 10^{7}\ M_{\odot}\ \mathrm{yr}^{-1}$, or $6 \cdot 10^{15}\ \mathrm{kg\ s^{-1}}$, we find that the energy released (assuming a 10% efficiency) is

$$L = PE \times \dot{M} =\sim 2 \cdot 10^{30}\ \mathrm{J\ s^{-1}} \tag{20.13}$$

As this energy will be released as heat energy, the radiation will have a thermal spectrum given by

$$L \simeq 4\pi R^2 \sigma T^4 \tag{20.14}$$

Resulting in $T \sim 10^7$ K, resulting in a blackbody spectrum that peaks in the X-rays.

To find black holes, we therefore need to look for single-lined spectroscopic binaries and X-ray emission.

Good black hole candidates are Cygnus X-1 $\left(M \geq 6M_{\odot}\right)$ and V404 Cyg $\left(M \geq 8M_{\odot}\right)$.

X-Ray observations of X-ray binary star systems containing either pulsars or invisible objects with $M \geq 3\ M_{\odot}$ has shown that $L_X(\mathrm{pulsar}) \geq 100\ L_X(\mathrm{unseen})$.

In pulsar systems, the X-rays are generated by material falling onto the surface of the neutron star. In the systems with a black hole, the matter disappears through the event horizon, and the lack of physical surface upon which matter impacts leads to a decreased X-ray luminosity relative to the pulsar systems.