Lecture 17: Stellar evolution –

Degenerate stars: pulsars and black holes

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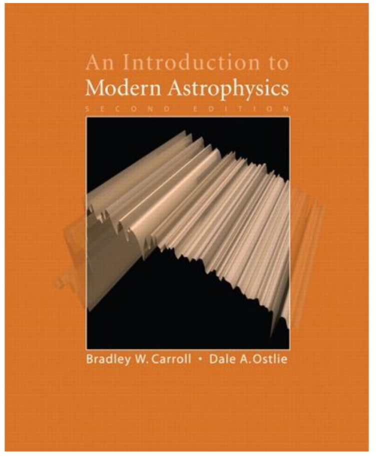
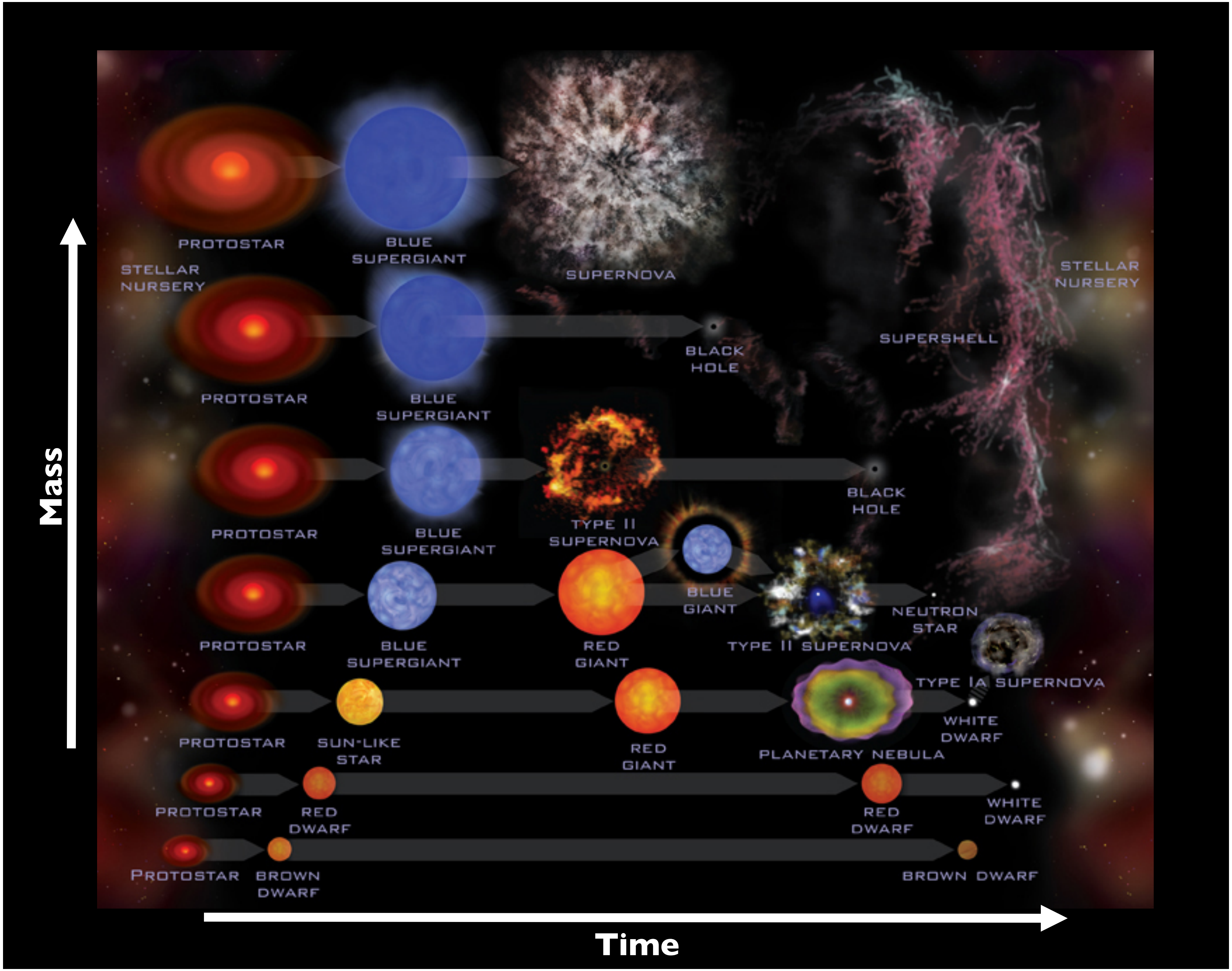
Chapters 16 & 17 of Carroll and Ostlie





Mass
Time
PROTOSTAR
BLUE SUPERGIANT
SUPERNOVA
STELLAR NURSERY
STELLAR NURSERY
PROTOSTAR
BLUE SUPERGIANT
BLACK HOLE
SUPERSHELL
PROTOSTAR
BLUE SUPERGIANT
TYPE II SUPERNOVA
BLACK HOLE
PROTOSTAR
BLUE SUPERGIANT
RED GIANT
BLUE GIANT
TYPE II SUPERNOVA
NEUTRON STAR
TYPE IA SUPERNOVA
PROTOSTAR
SUN-LIKE STAR
RED GIANT
PLANETARY NEBULA
WHITE DWARF
PROTOSTAR
RED DWARF
RED DWARF
WHITE DWARF
PROTOSTAR
BROWN DWARF
BROWN DWARF

Aims of lecture

Key concept: conservation of angular momentum

<u>Aims:</u>

- Understand why pulsars are believed to be rotating neutron stars due to the collapse of the stellar core of massive stars

- Be able to show that the minimum rotation period of a pulsar is:

$$P_{\min} = \left(\frac{3\pi}{G\rho}\right)^{1/2}$$

Period-density relationship

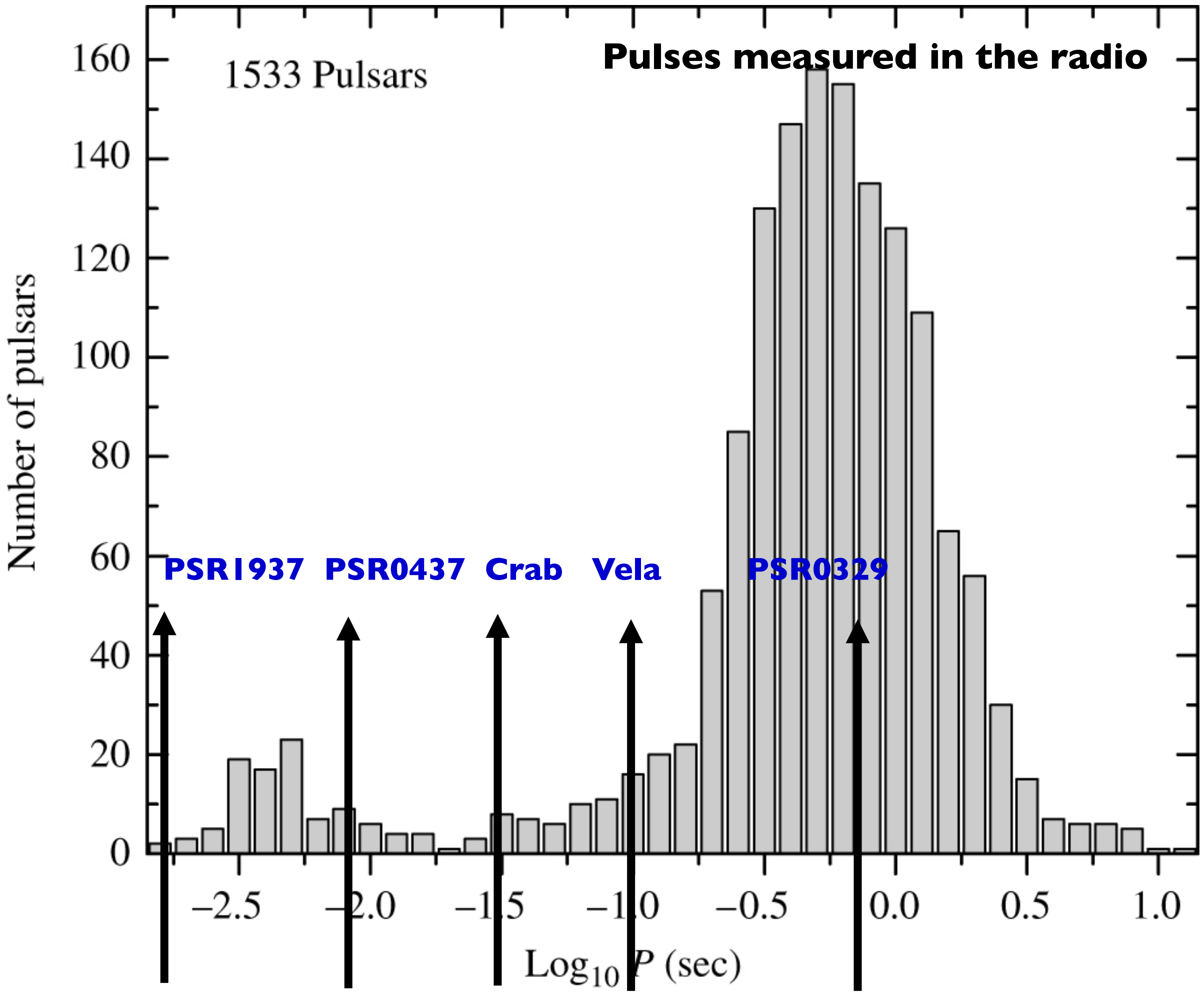
- Know and be able to show:

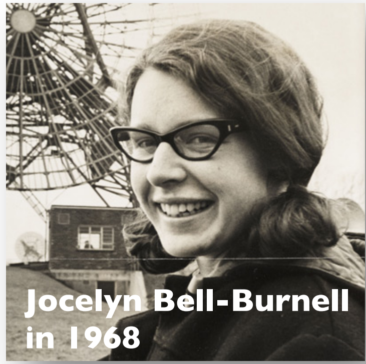
$$R_S = \frac{2GM}{c^2} = 2.95\left(\frac{M}{M_{Sun}}\right)km$$

Schwarzschild radius

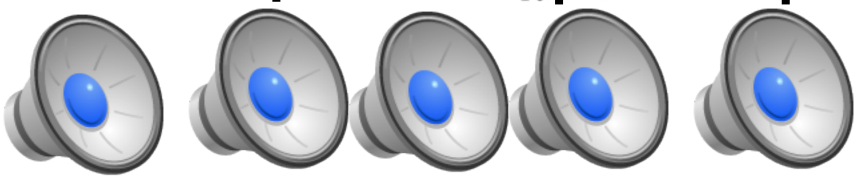
Pulsars: discovery and properties

Pulsars: one of the most significant astronomical discoveries winning the 1974 Nobel prize - not for the discoverer (research student Bell-Burnell) but for her supervisor!





Average period:
P~0.5 secs



Several thousand pulsars discovered in our galaxy: likely <1% of the total pulsar population (>100,000)!

Pulsars: general characteristics

1) Most pulsars have periods of between 0.25 and 2 seconds. The pulsar with the longest period is PSR1841+0456 (P=11.8s); the fastest is PSR1748-2446ad (P=0.00139s or 1.39ms)
2) Pulsars have very well defined pulse periods and make accurate clocks. The period of PSR1937+214 has been determined to be 0.0015578064488727 5 seconds!
3) The periods of pulsars increase very gradually as the pulses slow down. The rate of increase is given by the period derivative $\dot{P} \equiv dP/dt$. The rate of the increase is typically $\dot{P} \sim 10^{-15} ss^{-1}$.

There were originally several possible origins for pulsars:
(1) binary stars, (2) pulsating stars, (3) rotating stars, (4) aliens???

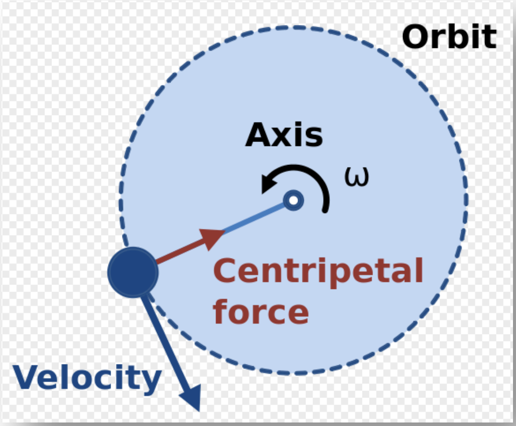
But early on it became clear that pulsars are rotating stars (a minority are binaries). Given how short the periods are, the rotation must be extremely fast. What types of stars are they?

Pulsars: what are they?

The angular velocity, ω, is limited by the ability of gravity to supply the centripetal force which keeps the star from flying apart. This constraint is most important at the star's equator, where the stellar material moves most rapidly.

Ignoring any equatorial bulging caused by rotation, for a star with radius R and mass M, the maximum angular velocity can be found by equating the gravitational and centripetal accelerations at the equator:

$$\omega_{\max}^2 R = \frac{GM}{R^2}$$



If we assume uniform density, then:

$$\omega_{\max}^2 R = \frac{G}{R^2} \rho \frac{4}{3} \pi R^3$$

Since ω=2πf, where f is the frequency of rotation, then P=1/f

Pulsars: what are they?

Inserting this into the previous equation we therefore get

$$\frac{4\pi^2 R}{P^2} = \frac{4}{3} G\rho\pi R$$

Rearranging:

$$P_{\min} = \left(\frac{3\pi}{G\rho}\right)^{\frac{1}{2}}$$

Equation 29

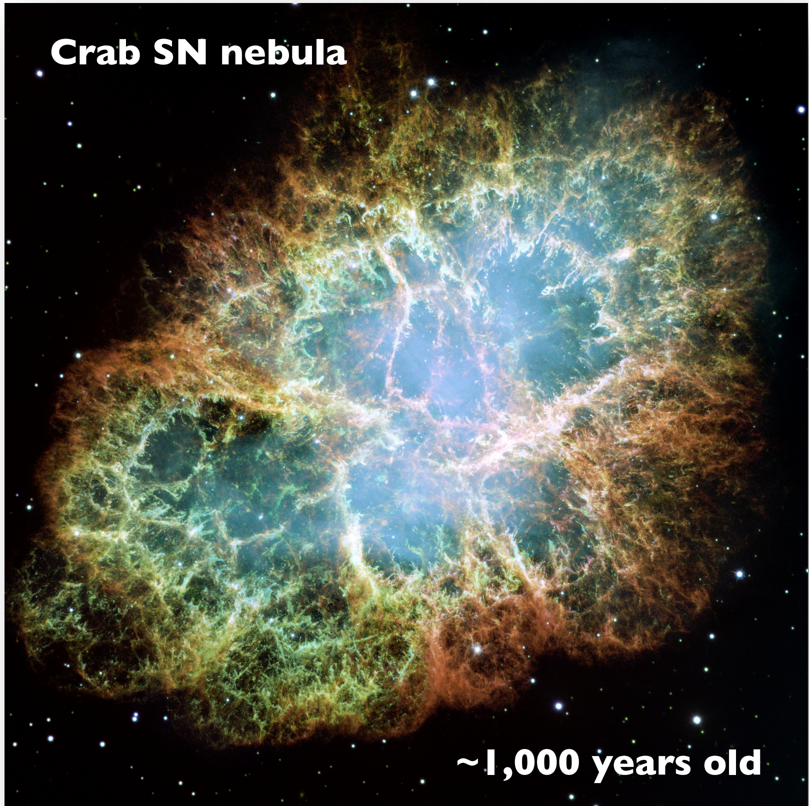
The limit on rotational angular velocity is actually more severe than this, because the star will distort into an ellipsoid and tend to lose material in a disk-like extension of the equatorial region.

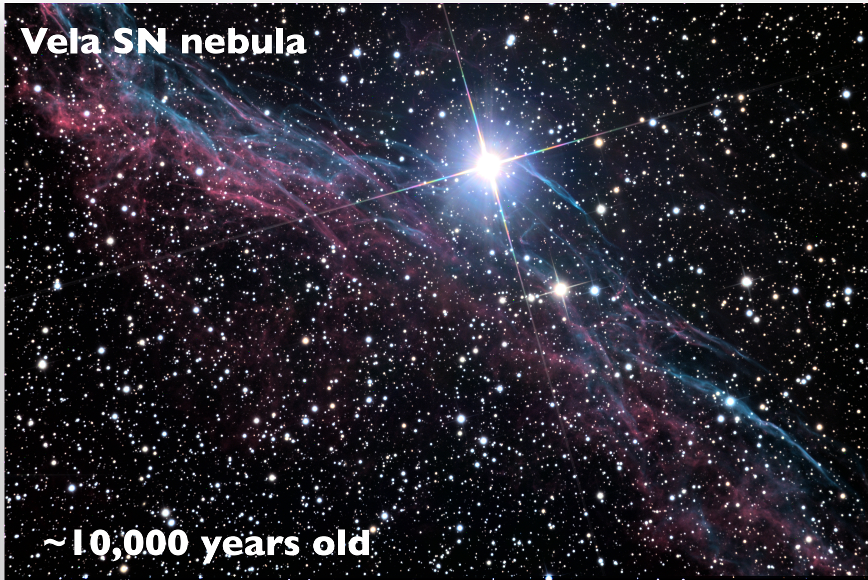
For the density of a white dwarf ($\sim 10^9$ kg m^{-3}), the minimum rotation period is ~12 s, which is too long for typical pulsars. However, for a neutron star density ($\sim 10^{18}$ kg m^{-3}), the minimum rotation period is $\sim 4\times10^{-4}$ s, which would allow for all of the observed periods of pulsars

The majority of pulsars are therefore likely to be rotating neutron stars

Pulsars: what are they?

A strong neutron-star connection is also found from their association with supernovae. Pulsars are found at the centres of both of these supernovae





The rapid rotation of a pulsar is thought to be due to the conservation of angular momentum from the collapse of the core (producing the neutron star) after fusion has ceased (see lecture 15)

Pulsars: current model – collapsed stellar core

When the core collapses from an initial state (i) to a final state (f) it will conserve angular momentum:

$I_i\omega_i = I_f\omega_f$ and since $I = CMR^2$

I is moment of inertia

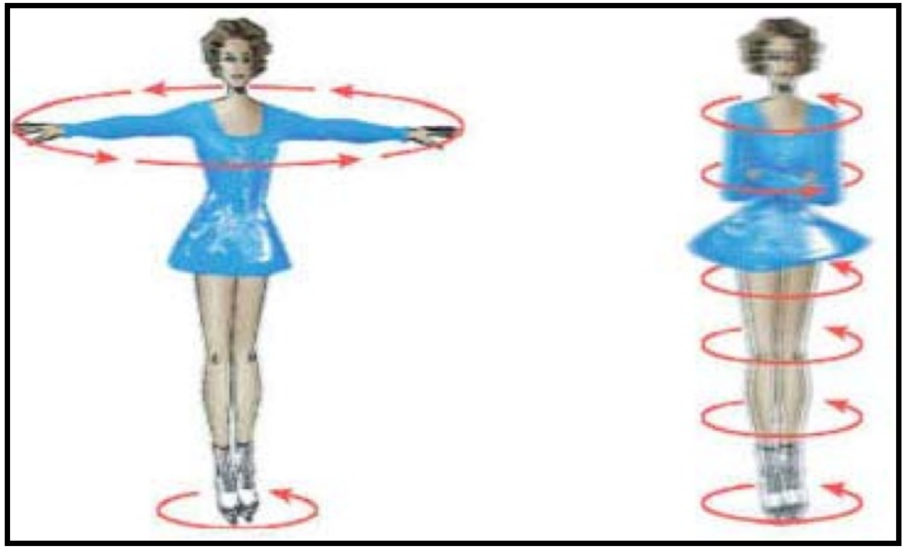
Assuming C (distribution of mass) and M remain constant then

$$\omega_f = \omega_i\left(\frac{R_i}{R_f}\right)^2$$

or

$$P_f = P_i\left(\frac{R_f}{R_i}\right)^2$$

in period



A stellar core of ~6,000 km (a typical size) with a period of ~1,800 sec would rotate at ~0.01 sec, when collapsed to a 15 km radius (typical for that of a neutron star)

The origin of the radio pulses is a huge magnetic field (~10^8 T) - dipole. The magnetic flux is also conserved during collapse, which causes a ~10^4-10^5 increase in strength!

Pulsars: current model – radio pulses

Formation of a magnetosphere

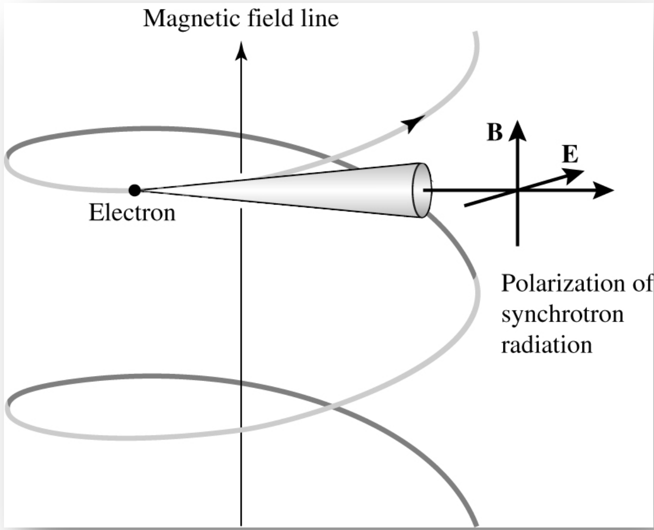
It is thought that the extreme magnetic field in a neutron star rips charged particles from the neutron-star crust and creates a "magnetosphere" of particles surrounding the star. Although the pull of gravity is extremely high the magnetic field dominates by a factor of $>10^9$ at the surface!

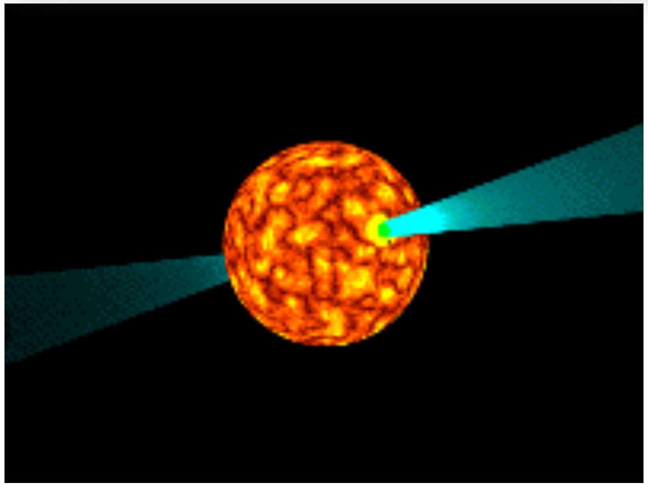
Production of the radio emission

The charged particles (in the magnetosphere) are accelerated to relativistic speeds along the field lines.

As they are accelerated they emit radiation in a narrow beam (called "synchrotron emission"; see figures), which is what we observe as a radio "pulse". The radio emission is just a small fraction of the total energy released.

Synchrotron emission

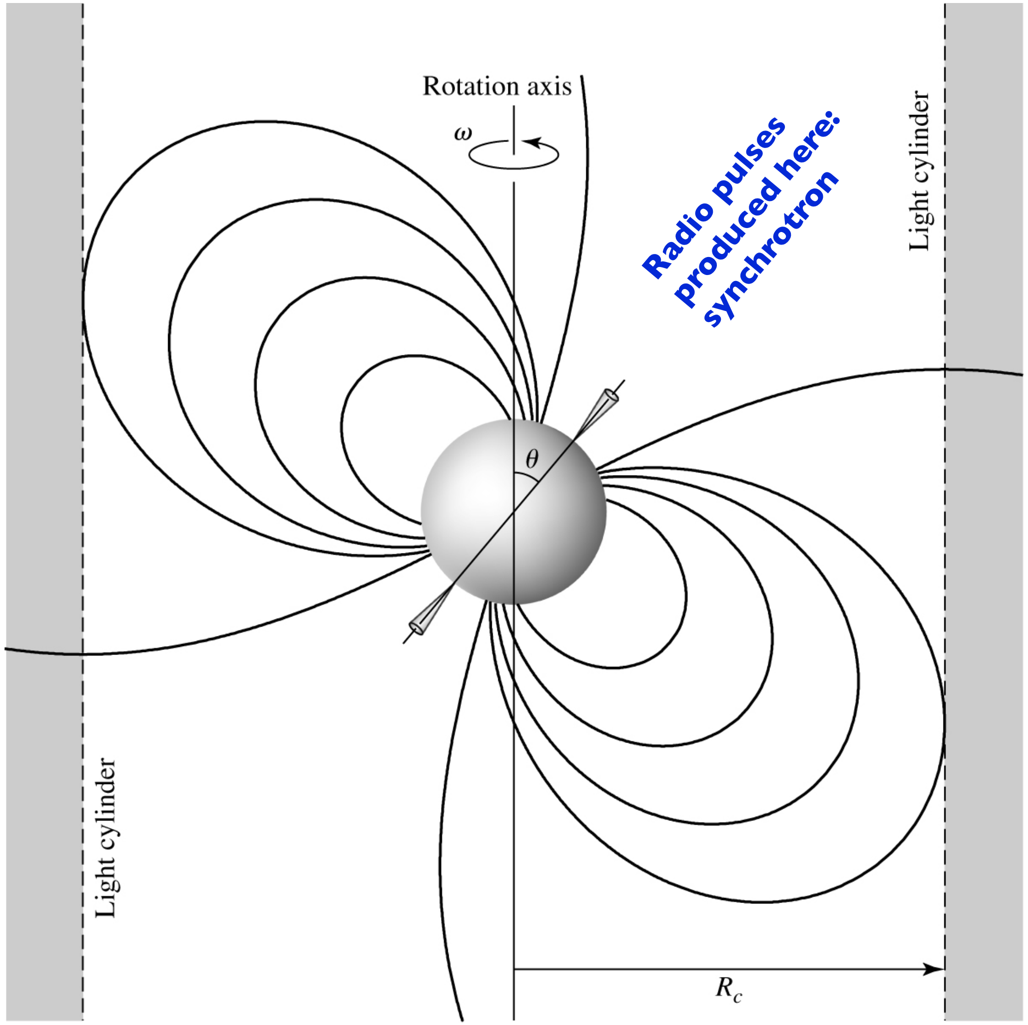




Because the radio pulses are emitted in a narrow beam only a fraction of neutron stars are detected as pulsars

Pulsars: origin of the radio pulses

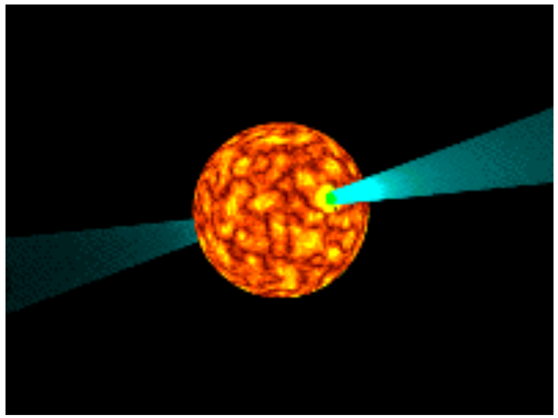
The origin of the radio pulses in a pulsar is a huge magnetic field (~10^8 T!) - dipole. The magnetic flux is conserved during collapse, which causes a ~10^4-10^5 increase in strength!



A local electric field is induced by the rotating magnetic field and is an overwhelming influence out to:

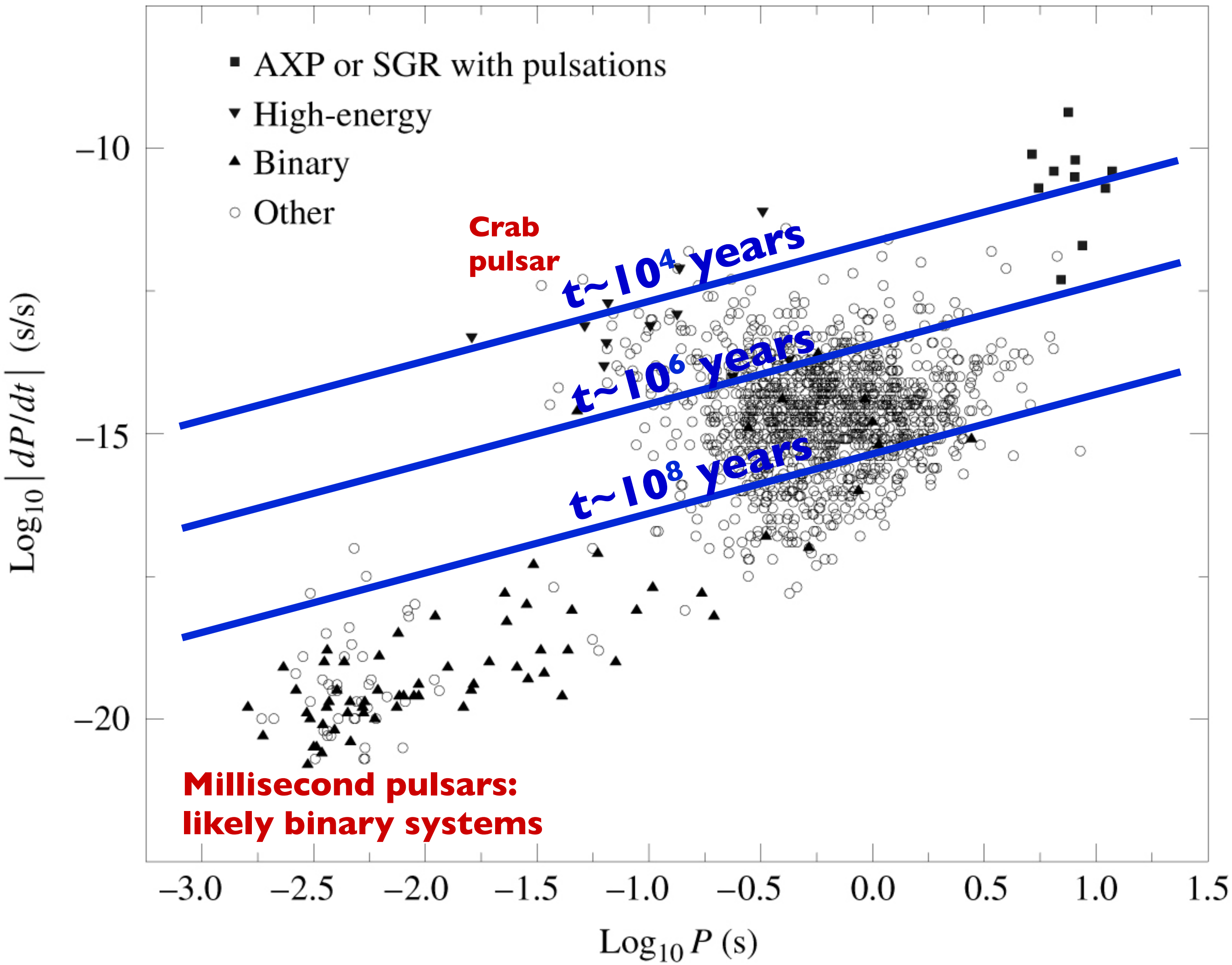
$$r_c = \frac{c}{\omega}$$

This defines the "light cylinder", the distance where a co-rotating extension would have a speed equal to the velocity of light, c



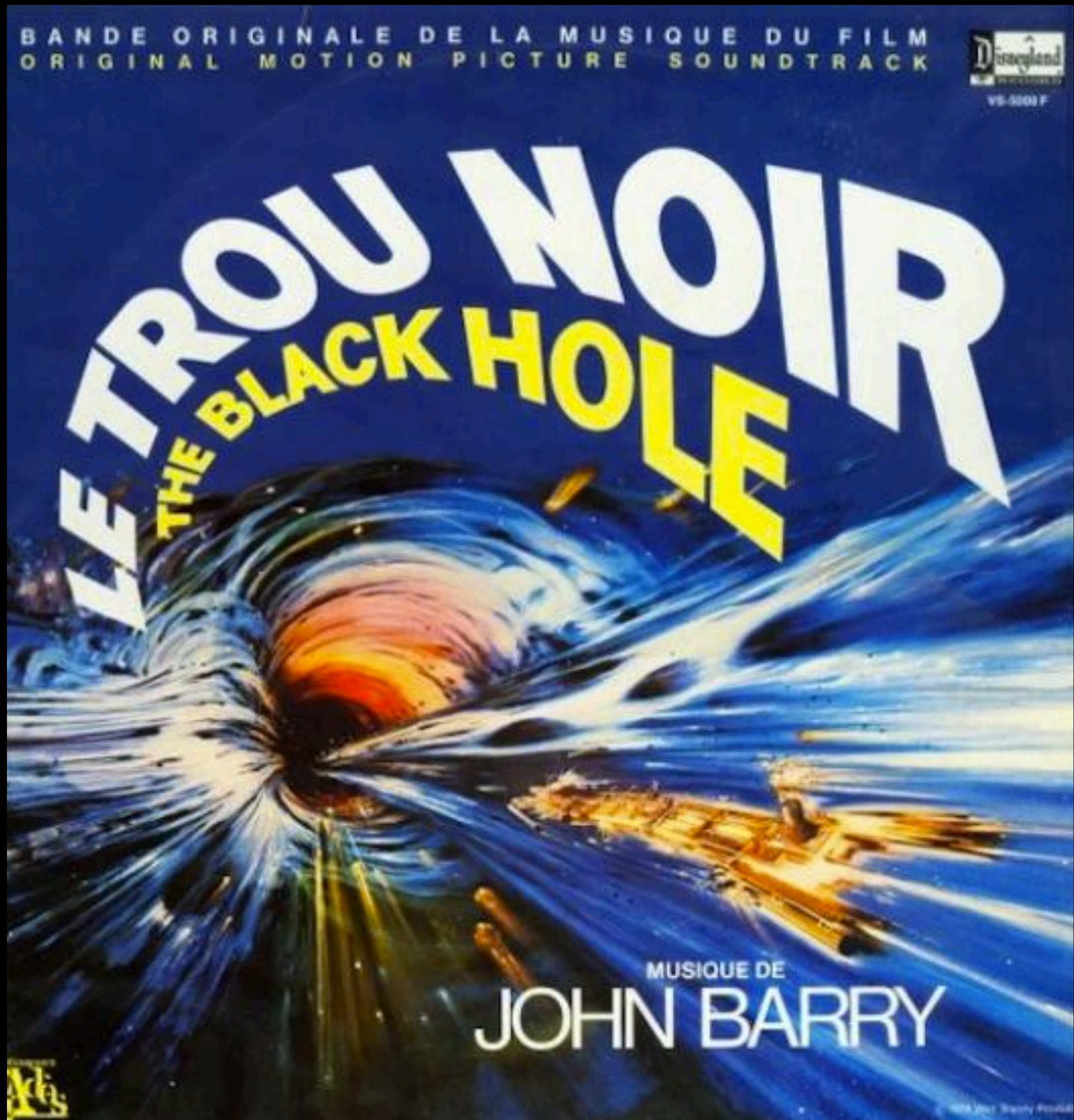
Pulsars: slowing down

This release of energy (the pulses) comes at a price: pulsars slow down with time



P and $\dot{P}$ also gives the "characteristic age" of the pulsar: $\tau \approx \frac{P}{\dot{P}}$

What if neutron degeneracy pressure fails?



Black holes: the ultimate fate

When the neutron degeneracy and strong force fails, currently no known force can prevent the object from total collapse. The object will become a black hole!

The standard laws of physics break down in a black hole but we can still define their exterior properties.

The existence of black holes was first suggested over 200 years ago (in 1783 by John Michell) but they still remain mysterious to us today. In a black hole the gravitational force is so high that not even light itself can escape. Hence no emission can escape from a black hole (the exception here is Hawking emission).

Any black hole can be described by just three numbers:

(1) Its mass **(initially defined by mass of collapsed core)**

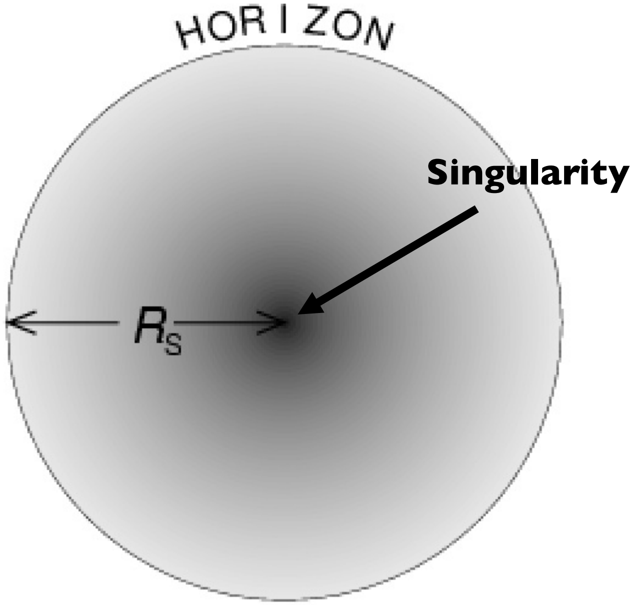
(2) Its angular momentum **(angular momentum conserved when collapse)**

(3) Its electric charge **(neutral in stars)**

A common expression is therefore "a black hole has no hair"!

Black holes: basic properties

To accurately characterise black holes requires using general relativity, which is beyond the scope of this course. However, we can make some general statements using classical physics about non-rotating black holes.



The radius of a black hole is defined when the escape velocity is the speed of light. Nothing within this radius can escape the black hole:

$$R_s \equiv \frac{2GM}{c^2} \approx 2.95\left(\frac{M}{M_\Theta}\right) \; km$$ **Equation 30**

This is also commonly called the Schwarzschild radius.

Nothing within the Schwarzschild radius can escape and so the Schwarzschild radius is also the location of the "event horizon" ("horizon" on this figure).

The density at the singularity is infinite and our laws of physics break down.

Black holes: basic properties

The radius of a black hole increases with mass unlike the situation for a white dwarf or a neutron star. However, the black-hole radius (the event horizon) does not represent an actual hard surface and so these are not equivalent measurements. The singularity at the centre of a black hole is of <u>infinite</u> density.

What would be the size of the Earth (event horizon) if it was crushed to a black hole?

About the size of
a sugar cube
but 6×10^{24} kg!

Range of properties for degenerate stars

Approximate range of properties expected for different degenerate stars

Degenerate state	Mass range (solar mass)	Radius (km)	Escape velocity (V_{esc})
White dwarf	~0.2-1.4	~2,000-14,000	~2,000-14,000 km s^{-1}
Neutron star	~1.0-2.5	~7-20	~0.4-1.0c
Black hole	>2.5	>7	>c!

$$V_{esc} = \sqrt{\frac{2GM}{R}}$$

These degenerate stars will slowly radiate away their energy. White dwarfs and neutron stars will cool leaving a cold dense ember. Black holes will emit Hawking radiation until they completely "evaporate"... but on extremely long time scales

However, the majority of the gas from stars goes back into the galaxy – this is the life cycle of stars