PHAS 1102
Physics of the Universe

6 – End points of stellar evolution

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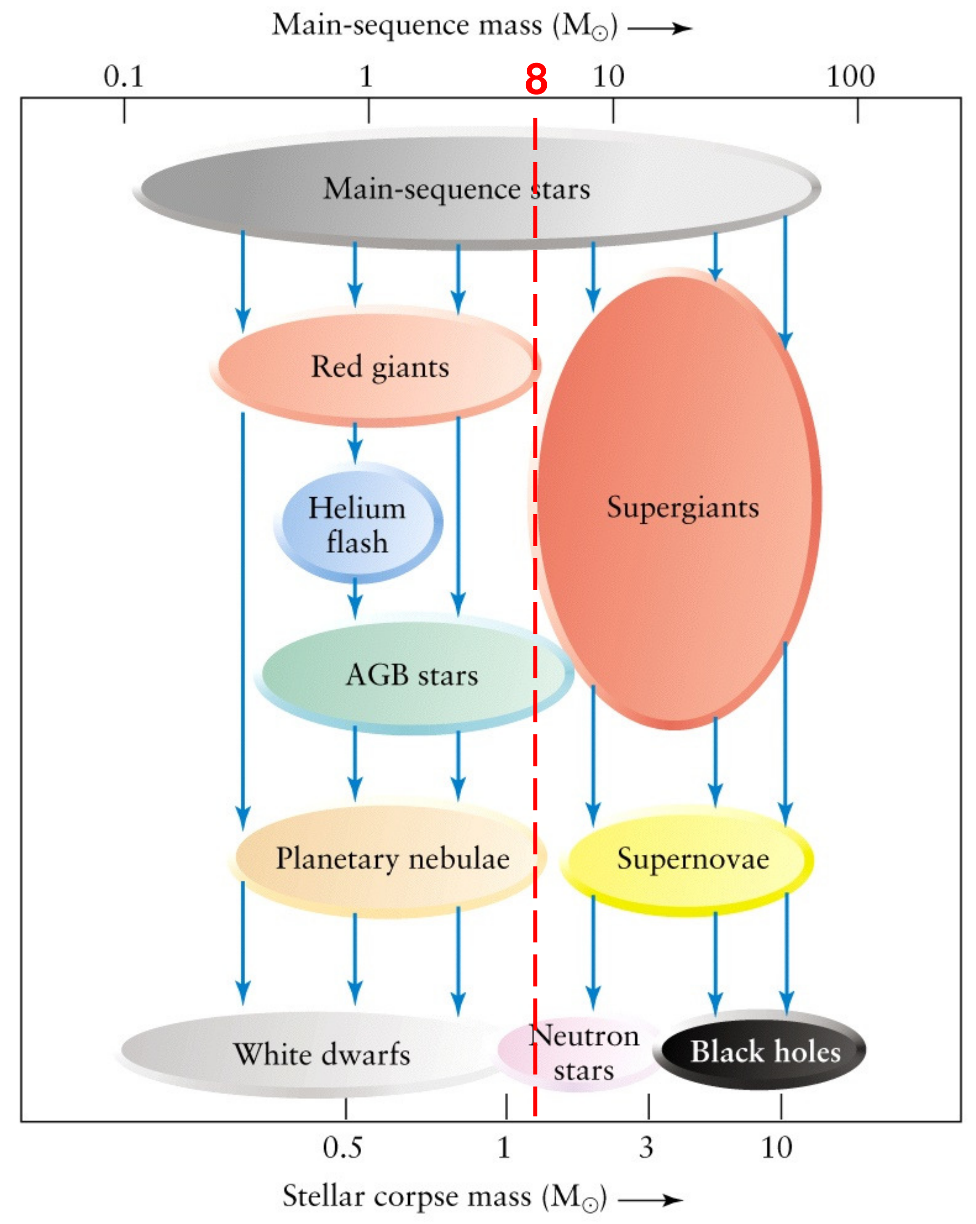
End points of stellar evolution *(ZG Ch. 17; FK Ch. 22)*

Kind of stellar remnant left over after post-MS evolution depends on the core mass at death (which is less than star's MS mass, because of mass lost in RG phase, PN or SN):

Remnant	Core mass at death (in solar mass)
White dwarf	< 1.4
Neutron star	> 1.4 but < 3
Black hole	> 3



White dwarfs

Planetary nebula core, after loss of outer envelope, shines as a very hot, dense star: a white dwarf

What kind of white dwarf?

MS mass	
< 0.5 solar	No He ignition → He white dwarf
> 0.5, < 5 solar	No C ignition → C - O white dwarf
> 5, < 8 solar	Can burn C → O - Ne - Mg white dwarf

Typical properties:

Mass = 0.7 solar mass

Radius = 0.01 solar radius = 7×10^6 m

Average density = 10^9 kg m^{-3}

In a few 10^9 yrs , thermal energy radiated away → black dwarfs (would be very difficult to detect, temperature just above 2.7 K microwave background; perhaps through gravitational effects?)

Degenerate electron gas

White dwarfs supported by electron degeneracy

Electrons are degenerate according to Pauli's Exclusion Principle (law of Quantum Mechanics,1925): Two electrons cannot occupy simultaneously the same quantum state (i.e. two things cannot be in the same place at the same time), so they get so packed together that a limit to further compression is reached.
Quantum state: Particular set of circumstances concerning locations and speeds that are available to particles

Electrons distributed more or less uniformly around nuclei, which are also tightly constrained as pressure increases, similar to crystalline lattice (like a solid rather than a gas)

Chandrasekhar limit

White dwarfs have peculiar properties, e.g.
as mass increases, radius decreases (mass-radius relation)

➔Ultimate mass limit for white dwarfs:
Chandrasekhar limit of ~ 1.44 solar mass = 3 x 10^{30} kg

In a contracting stellar remnant with > 1.44 solar mass, degenerate electron gas pressure cannot hold gravity off
→ Matter crushed to such high densities that

$$p + e^- \rightarrow n + \nu$$

Protons and electrons squeezed into neutrons →
Degenerate neutron gas, which halts the collapse →

neutron star

This process is generally associated with the evolutionary end of massive stars and Type II SN

White dwarfs and General Relativity

White dwarfs provide test for Einstein's General Relativity: Their surface gravity is high enough to produce a detectable gravitational redshift in their spectral lines.

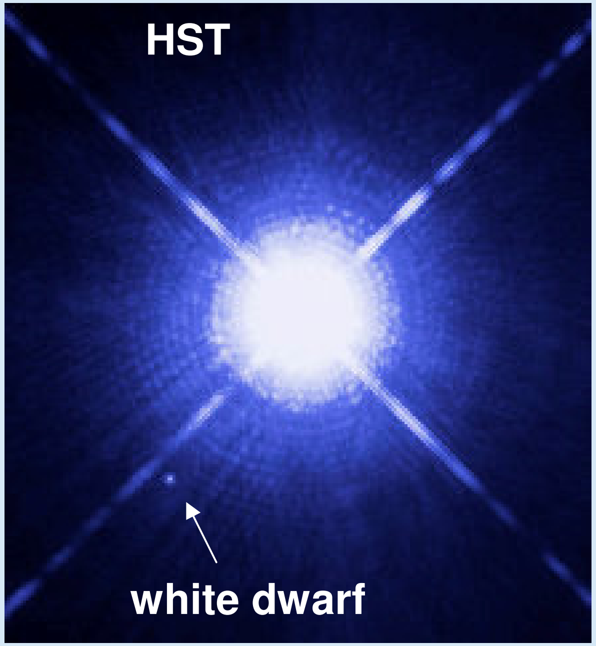
Gravitational redshift: Light must do some work to emerge from a body with a strong gravitational field - photon has an 'equivalent mass' (from $E = h\nu = mc^2$) and gravity affects it → Photons lose energy and suffer a decrease in frequency (an increase in wavelength)

→ Gravitational redshift depends on mass-to-radius ratio: larger the ratio, larger the gravitational redshift

Complicated by star's intrinsic motion → easier to separate the two if star is in a binary system

Sirius A and B

Sirius (α Canis Majoris), brightest star in the night-time sky, $m_V = -1.47$; binary star system consisting of blue-white MS dwarf star (Sirius A) + faint white dwarf companion (Sirius B)



Sirius B parameters: Mass = 1.05 solar mass

Radius = 7 x 10^{-3} solar radius

T_{eff} = 29,500 K

Measured gravitational redshift 3.0 x 10^{-4} $\Leftrightarrow$ expected 2.8 x 10^{-4}

Supernova Type Ia

White dwarfs may also exceed the Chandrasekhar limit through accretion (a few white dwarfs are in binary systems with non degenerate companions)

→ This triggers thermonuclear detonation which destroys the white dwarf, producing very luminous SN Type Ia (from C - O white dwarf progenitors)

→ Lightcurves follow decay of ^{56}Ni and ^{56}Co

Small dispersion in maximum luminosity → good ‘standard candles’ for extragalactic distance scale
→ HST ‘Key Project’ to determine expansion rate and age of the Universe (see second half of the course)

Neutron star properties (ZG Ch. 17; FK Ch. 23)

Typical properties:

Mass = 1.5 solar mass
Radius = 10 km
Average density = 10^{17} kg m^{-3}
Escape velocity ~ 0.8 c

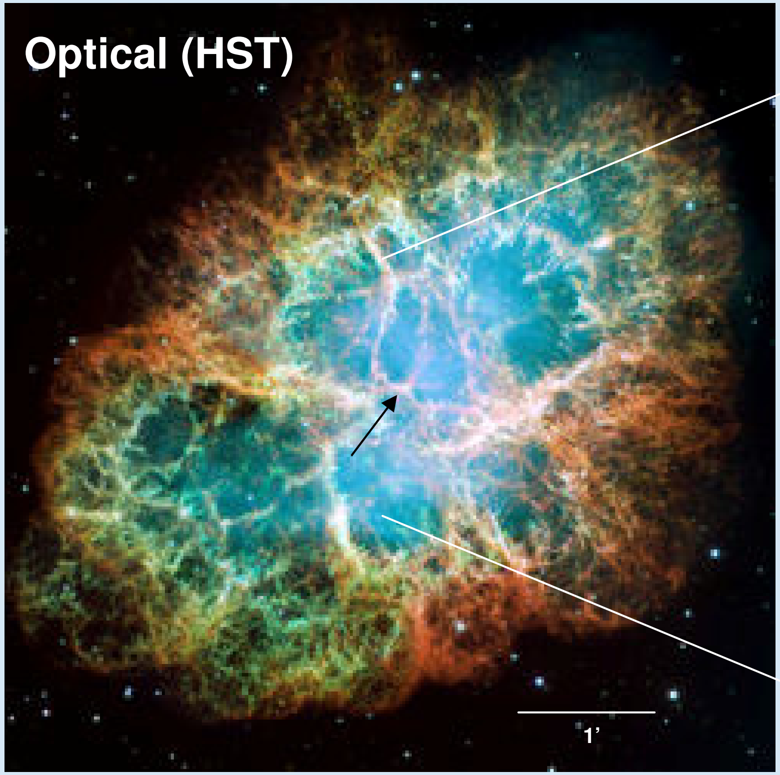
Neutron stars have very low intrinsic luminosities
→ hard to see isolated neutron stars, except in special circumstances … like as pulsars

Pulsar is a rotating, magnetic neutron star (i.e. the star itself does not pulse)

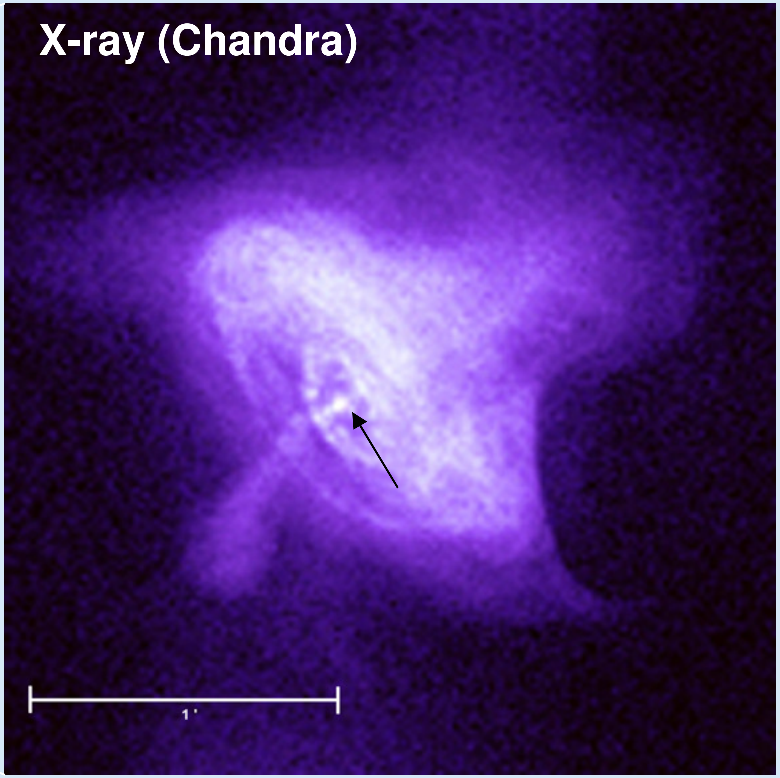
When star collapses, angular momentum and magnetic field strength are conserved → neutron star rotates very rapidly and has strong magnetic field (~ 10^8 Tesla ~ 2 x 10^{11} solar)

A special SNR with pulsar: the Crab Nebula

SN1987A neutron star not yet observed: expected to become visible in X-rays in ~30 yrs (when expanding outer layers become 'optically thin').
However, most famous historical Supernova exploded in 1054 (Chinese records) to leave the Crab SNR and pulsar (thought to be the neutron star remnant of the exploded star).



$P_{\mathbf{pulsar}}$= 33 ms!



The Crab Nebula

Distance (~ 2 kpc) and age (~ 950 yrs) estimated from rate of expansion of gaseous shell. Pulsar's slow down: ~ 4 $x10^{-6}$ s yr^{-1}

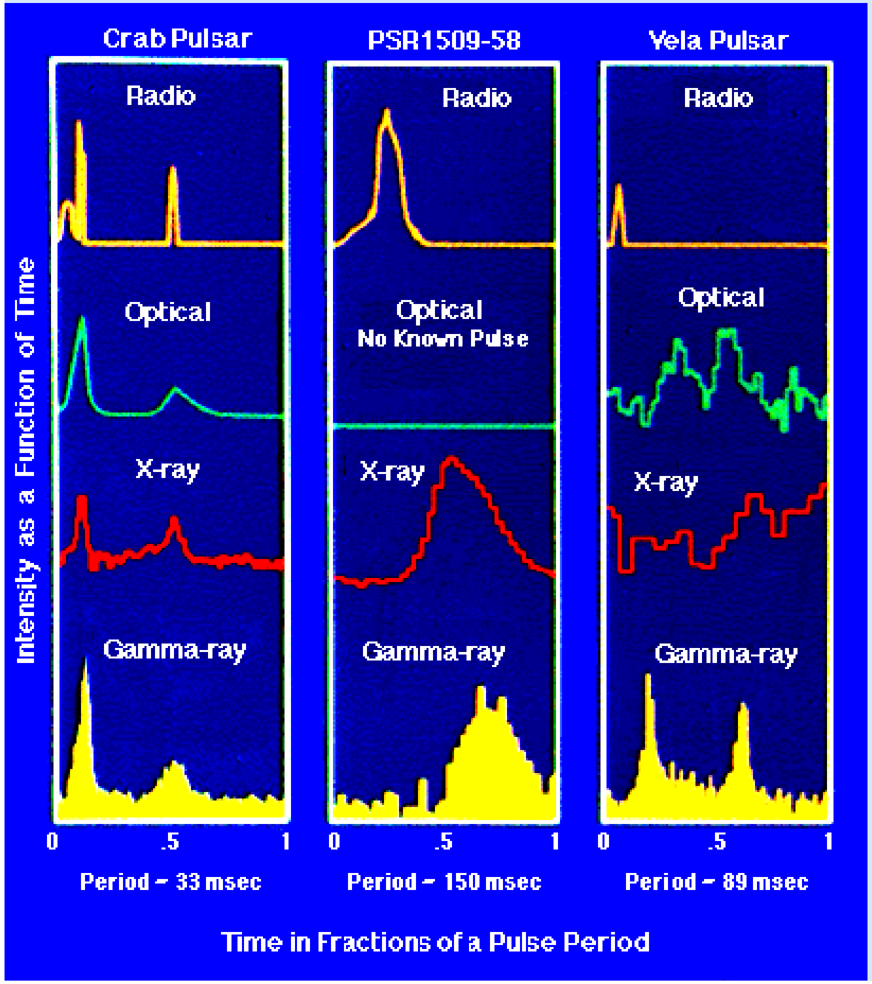
Visible line emission from filaments (gas density higher)
Nebula and pulsar are strong radio and X-ray sources

Underlying radio-to-X-ray continuum strongly polarised
→ non-thermal (i.e. non-blackbody) synchrotron radiation from relativistic electrons moving in a magnetic field (5 x 10^{-8} Tesla in the nebula); higher the electron energy, higher the radiation frequency

Where do relativistic electrons come from? (need powerful energy source) → The pulsar!
Nebula energetic output decreases in line with pulsar spin-down rate: rotational energy loss → radiation

Discovery of pulsars *(ZG Ch. 17; FK Ch. 23)*

Majority of pulsars (~1500 pulsars by 2004) discovered as radio sources (since 1967, Hewish & Bell Burnell, Cambridge → 1974 Nobel Prize)



For a given pulsar, period keeps very accurately (better than 1 part in 10^8)

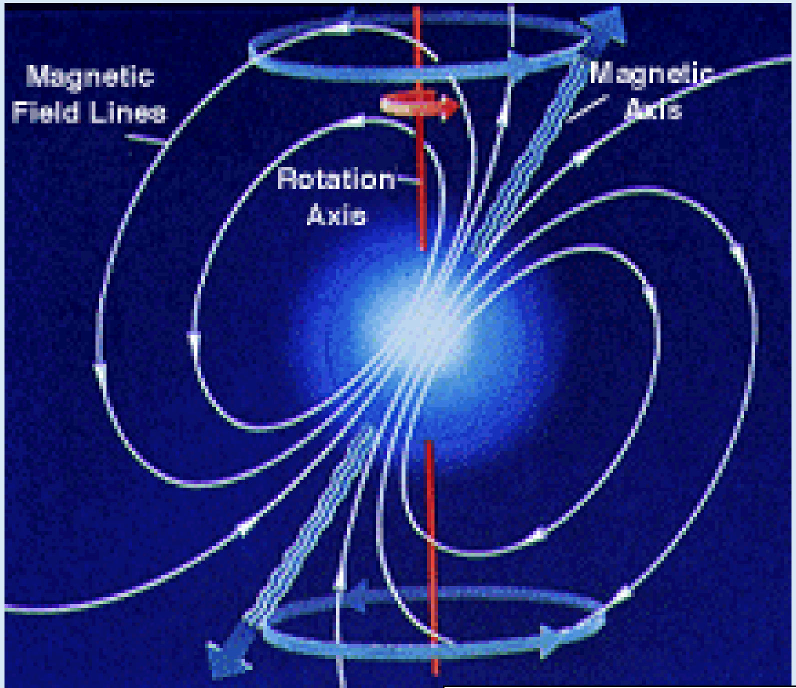
Amount of energy in pulses varies considerably (some pulses missing). Intensity and shape vary between pulses, average has unique shape.

Period range: 1.6×10^{-3} - 4.0 s

Typical spin down by 10^{-8} s yr^{-1}
➔ age from period/spin down

'Lighthouse' model for pulsars

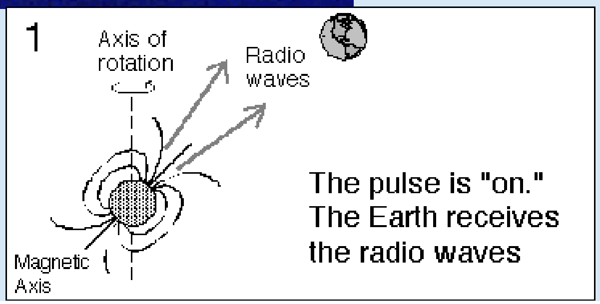
As pulsar spins, magnetic field induces huge electric field which rips electrons off its surface and accelerates them to relativistic speeds → electrons spiral around magnetic field lines → synchrotron radiation in a tight beam from the magnetic poles



Pulsar model

If magnetic and rotation axes are not aligned, and rotation axis is roughly aligned with the Earth, we see bursts of radiation every rotation

→ lighthouse effect



Pulsar's rotational energy is radiated away →
pulsar must spin down

Supernovae, Gamma-Ray Bursts and black holes

Supernovae

Type Ia – White dwarf exceeds the Chandrasekhar limit through accretion → neutron star

Type Ib and Ic – Cores of very massive stars, which have lost most of their outer layers through intense stellar winds, collapse after running out of nuclear fuel (may also be called 'hypernovae')

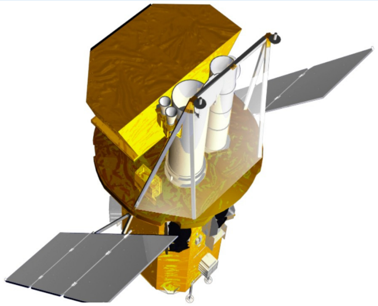
Wolf-Rayet stars → Type Ib → black holes

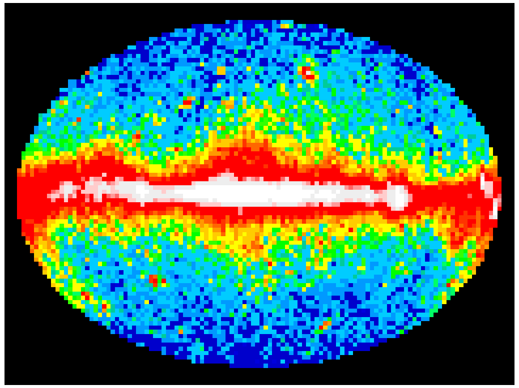
Some Type Ic, or even all Type Ib and Ic, may undergo a 'collapsar' stage: fast rotating core collapses to form a black hole, sucking in the surrounding material → precursors of long (> 2 sec) Gamma-Ray Bursts

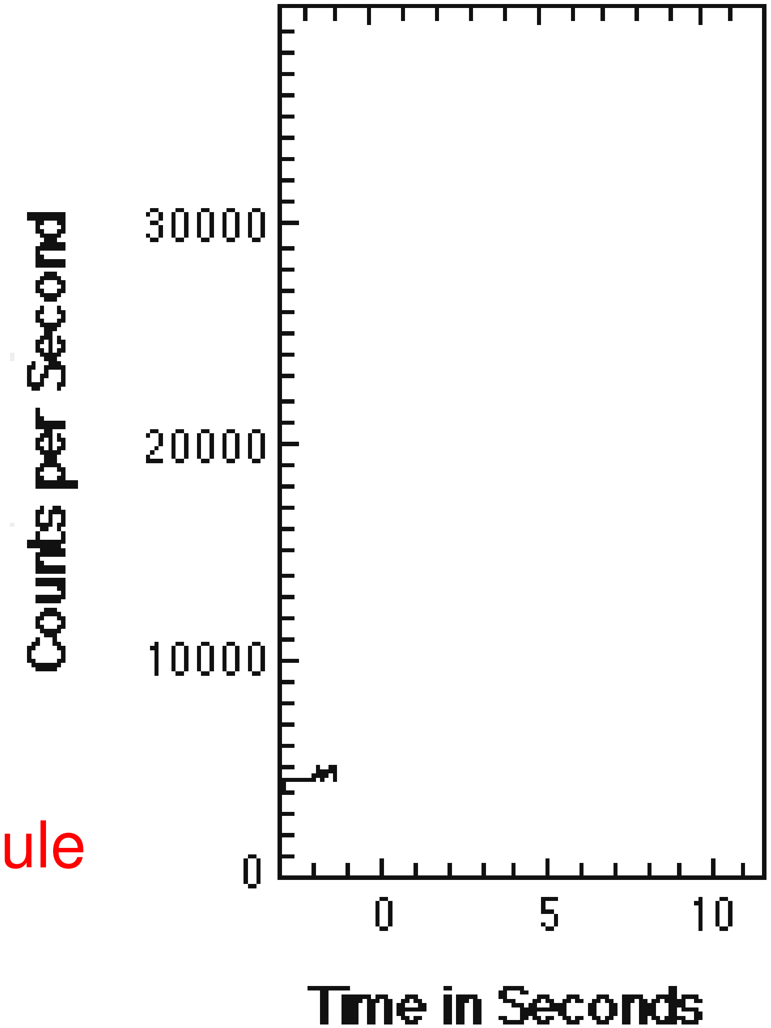
Type II – Core collapse of massive star (> 8 solar mass) → neutron star or black hole

What are Gamma-Ray Bursts?

Black hole births: Hypernovae (>2 s) or
coalescing neutron stars (< 2 s)







E = 10^{44} – 10^{47} Joule

Star collapse to a black hole *(ZG Ch. 17; FK Ch. 24)*

Similar physics applies to the collapse of neutron stars as it does to that of white dwarfs → neutron stars also obey a mass-radius relation and the upper limit to the mass is 3 solar mass →

Collapse of stars of > 3 solar mass (MS star > 20 solar mass) cannot be halted at the neutron star stage, but will go all the way to a black hole: volume decreases to zero, density becomes infinite to form a singularity.

A critical radius exists, called the Schwarzschild radius, where the escape velocity equals the speed of light ($\boldsymbol{G}$: gravitational constant; $\boldsymbol{M}$: black hole mass; $\boldsymbol{c}$: speed of light)

$$\boxed{R_{\mathrm{Sch}} = \frac{2GM}{c^2}}$$

Also called the event horizon → nothing can escape!

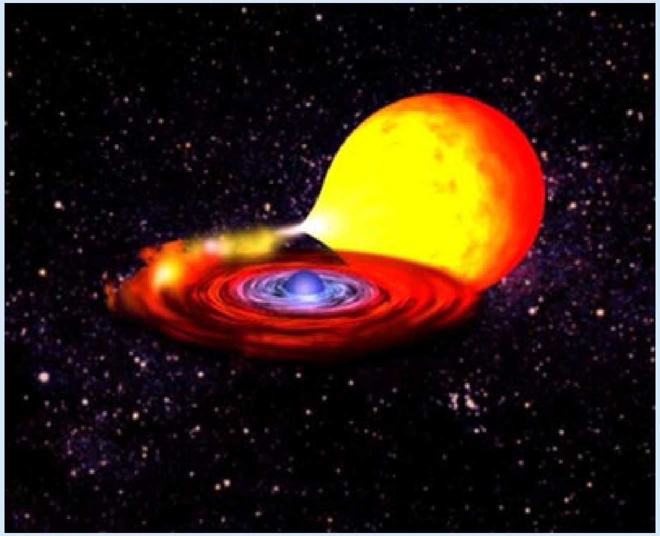
Black hole: Body that is all contained within its Schwarzschild radius

Observing black holes

An isolated black hole cannot be observed; we can only detect its influence on material around it: matter falling onto a black hole gains kinetic energy and heats up → ionised → radiates

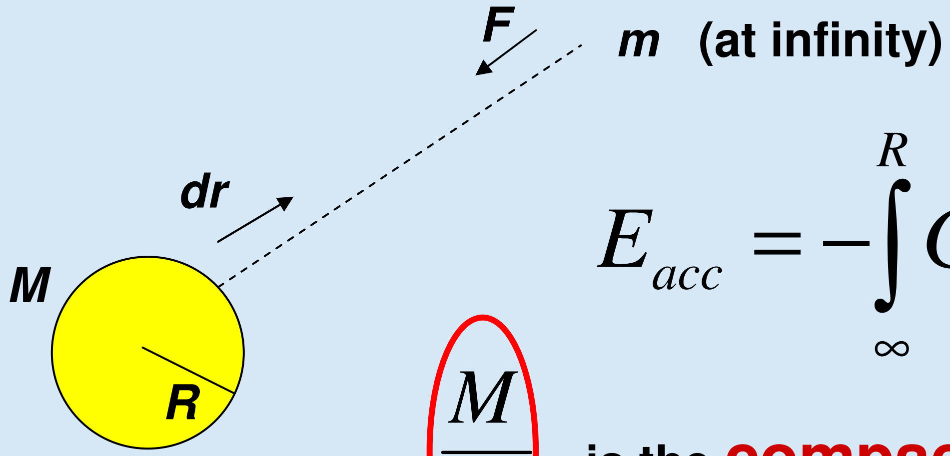
If temperature reaches few million K → X-rays

Most efficient if black hole has plenty of gas supply around, like in a binary system where the companion star fills its 'Roche lobe' (volume controlled by the gravity of the star)
→ Black hole's strong gravity draws gas from the companion → accretion



If accreted material has some angular momentum, it will form an accretion disk around the black hole; viscosity in the disk heats it up → X-rays

The physics of accretion



$$E_{acc} = -\int_{\infty}^{R} G\,\frac{Mm}{r^2}\,dr = \frac{GMm}{R}$$

$$\frac{M}{R}$$ is the **compactness**

→ White dwarfs, neutron stars, black holes

For a neutron star: $M = M_{\mathrm{Sun}}$ and R = 10 km

$E_{\mathrm{acc}} = 10^{16}$ Joule kg^{-1} ↔ $E_{\mathrm{nuc}} = 6 \times 10^{14}$ Joule kg^{-1}

Black hole candidate: Cygnus X-1 (ZG Ch. 18; FK Ch. 24)

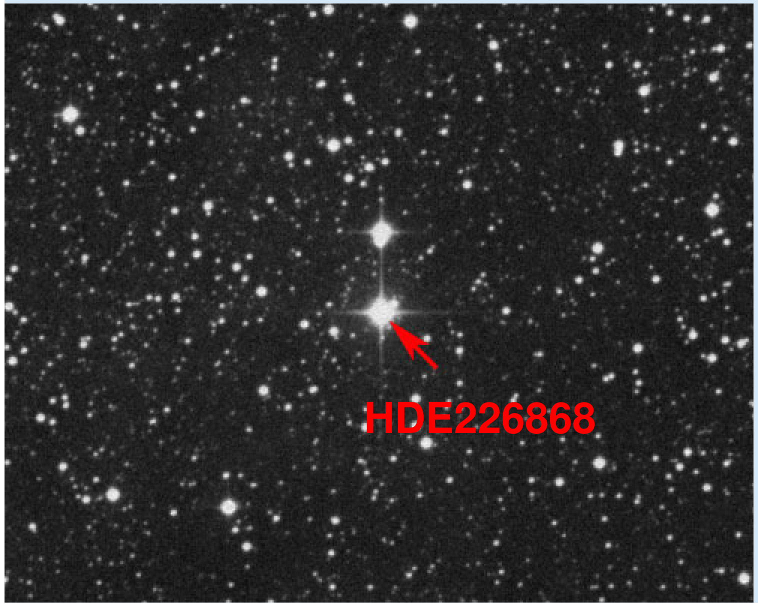
Bright X-ray source (2×10^{30} W) associated with HDE226868, an O supergiant star, in a binary with 5.6 day orbital period.

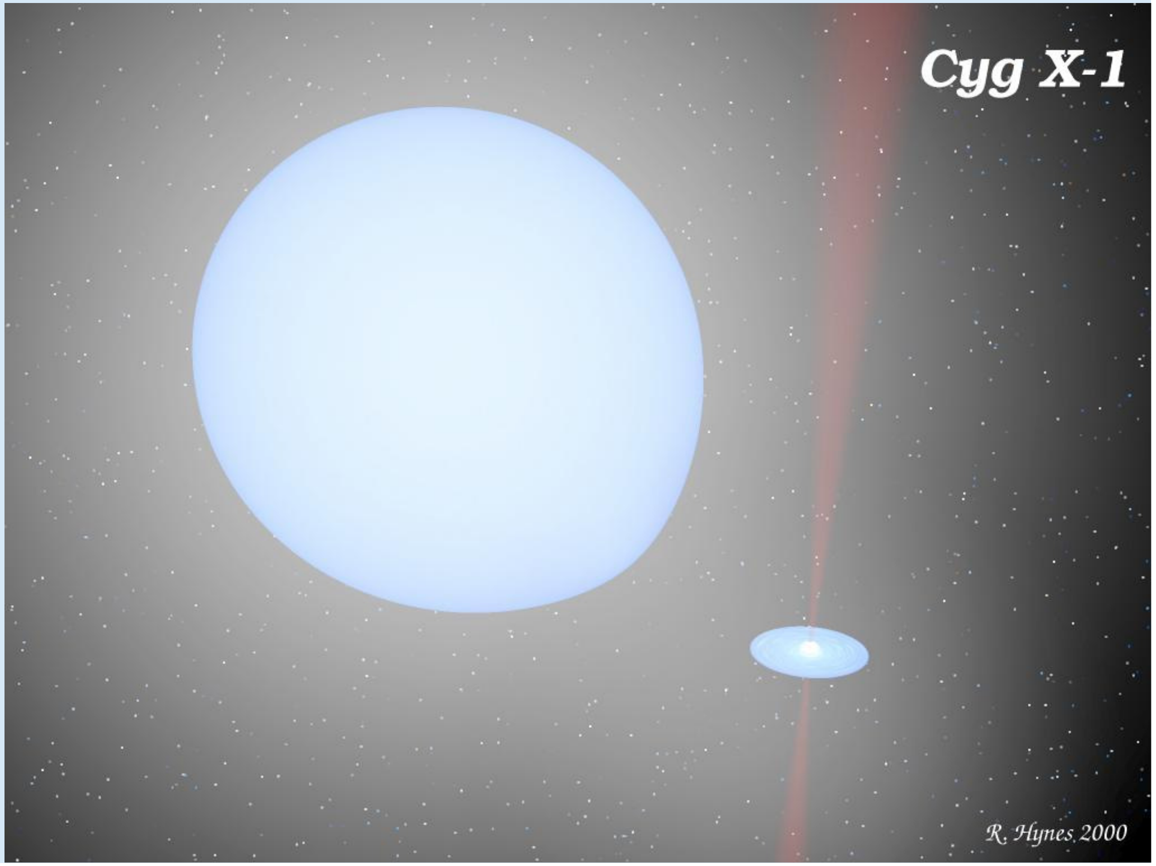
X-ray source flickers rapidly (< 0.001 s) → compact!

Mass function of the binary → if O star is of ~ 20 solar mass, Cyg X-1 must be ~ 8 - 10 solar mass (too large for neutron star)

→ black hole

A few other Galactic black hole candidates known





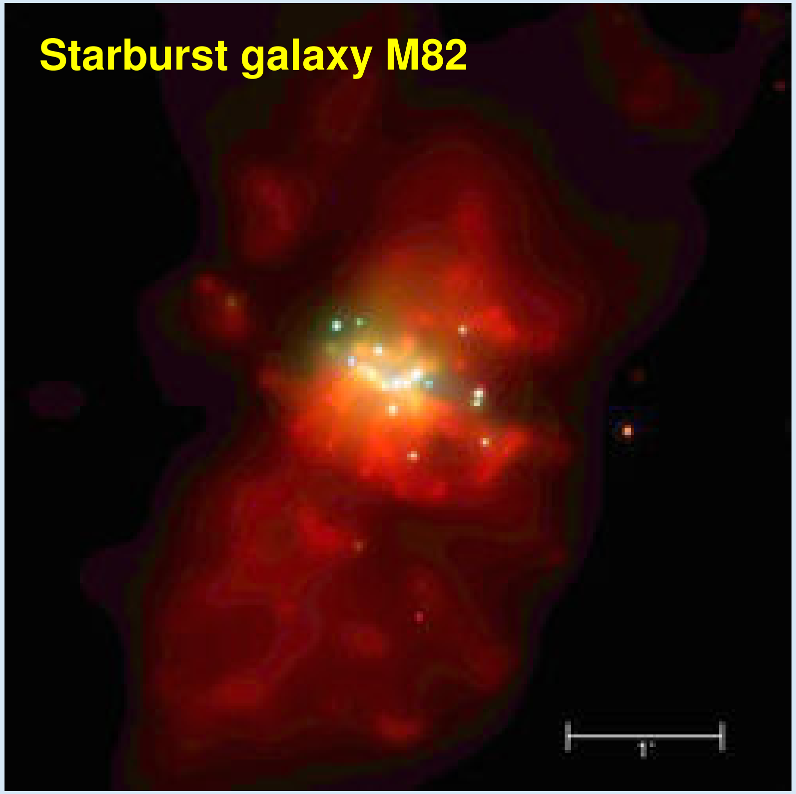
Ultraluminous X-ray sources

Luminosity of a star limited by pressure of the radiation it produces (photons, with $E = h\nu = mc^2$ and momentum $p = h\nu/c$)
→ stellar envelope can be blown off, or accretion in an X-ray binary stops
→ Eddington luminosity (L_{Edd}~ 10^{31} W for a 1 solar mass star)

ULX: Ultra-Luminous X-ray source, with luminosity >> L_{Edd} for a ~ 10 solar mass accreting black hole

Found in nearby galaxies other than the Milky Way

➔ 'Intermediate' mass black holes (100-1000 solar mass)?



Supermassive black holes in Active Galactic Nuclei

… are a scaled-up version of stellar size black holes

(10^6 – 10^9 solar mass black holes)

Lots more of exciting ‘Physics of the Universe’ to come!