Physics 521 - Astrophysics

Topics today: Supermassive Black Holes, Compact Binaries & Accretion

This week's reading: Chapters 17 & 18

Admin

Peer Review - Due Today Thursday, Nov 1

Homework #5 - Due Thursday, Nov 8, in class

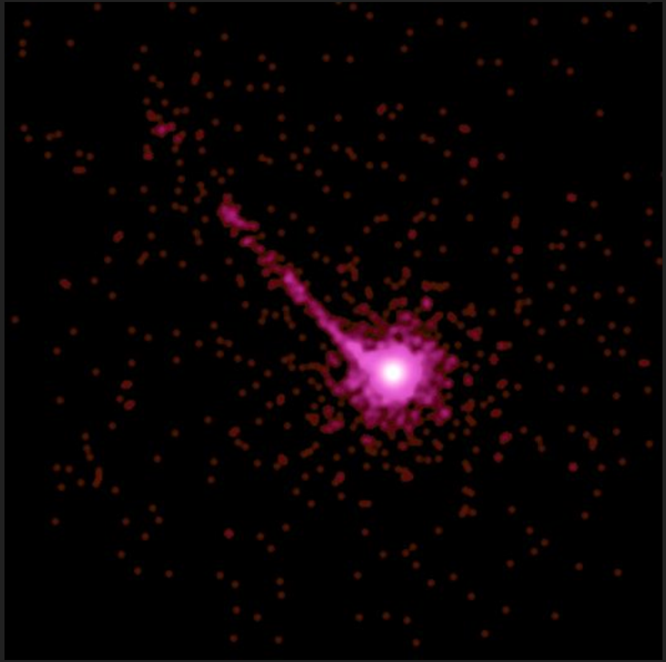
Supermassive BH

Topics covered in **last lecture**:

- death of massive stars
- formation of compact objects
- neutron stars and stellar mass black holes

Supermassive BHs

- QSOs were first observed in the 1960s and are found in the cores of massive galaxies.
- Their emission is powered by disk accretion. In accreting state SMBHs are referred to as **AGN** or **Quasars**.



Chandra X-ray image of Quasar PKS 1127-145 (NASA)

SMBH Formation

- Several theories exist on how SMBHs could be formed:
    - ‘Lumps’ in early Universe
    - ‘Stellar BH seeds’
    - Collapse of star clusters

Early-Universe ‘Lumps’

- Shortly after the **Big Bang** the Universe might have been **dense enough** for matter to form BHs.
- These seeds subsequently grow.
- **Enough matter** present for **galaxies** to grow around seeds.

‘Stellar BH Seeds’

- A SMBH could form from a **stellar mass black hole** of ~10 solar masses, which was produced by a supernova.
- This requires the surrounding environment to be sufficiently **rich in matter**.

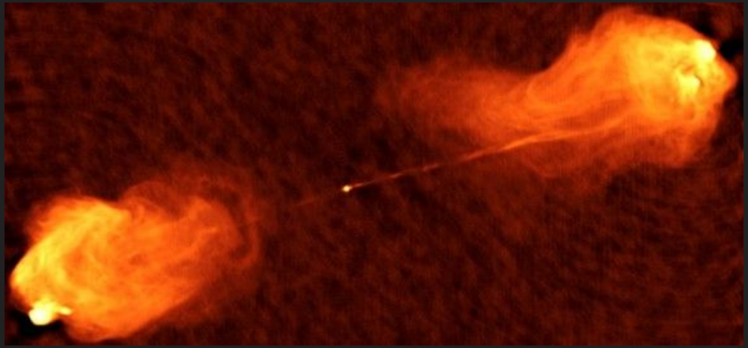
Star Cluster Collapse

HST image of globular cluster Messier 15 (NASA)

- If stars within a **tight** cluster were of similar size (above the Chandrasekhar limit), BH would form simultaneously.
- These BHs would absorb smaller stars and **eventually combine** to a SMBH.

Jet Formation

- Quasars show **giant jets** at multiple wavelengths.
- Particles from the disc fall towards the SMBH and are propelled outwards by the **magnetic field**.
- The particles move at almost the **speed of light** and emit **syn-chrotron radiation**.



VLA image of Cygnus A radio emission (NRAO)

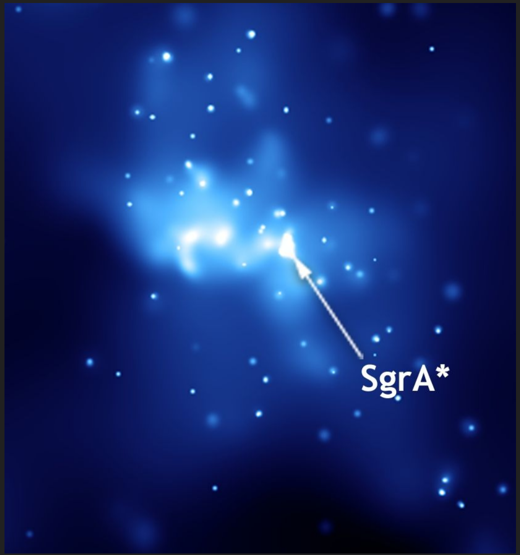
Cannibalism

- Quasars are only active for ~100 million years, but **'dead' quasars** could be revived with a **new food** source, i.e. by colliding with another galaxy.

- We observe colliding spiral galaxies. Milky Way and Andromeda have the same fate.

HST image of NGC 2207 & IC 2163 (NASA)

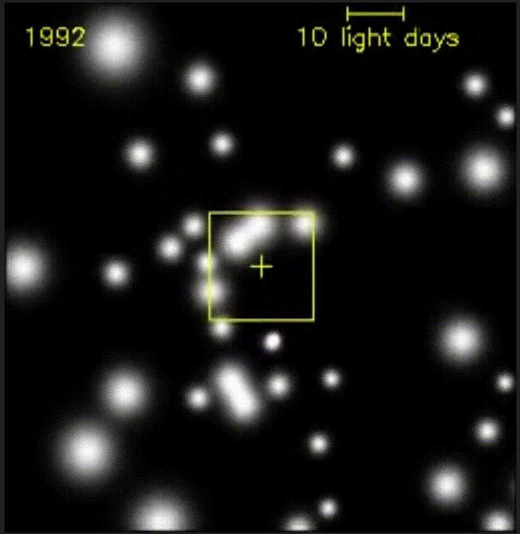
Our Galactic Centre



Chandra X-ray image
Sgr A* (NASA)

- Our view of the galactic centre is obscured by a lot of **dust/gas**.
- **Sgr A*** is a compact/bright radio source at the Milky Way's centre.
- The emission is likely coming from close to a SMBH.

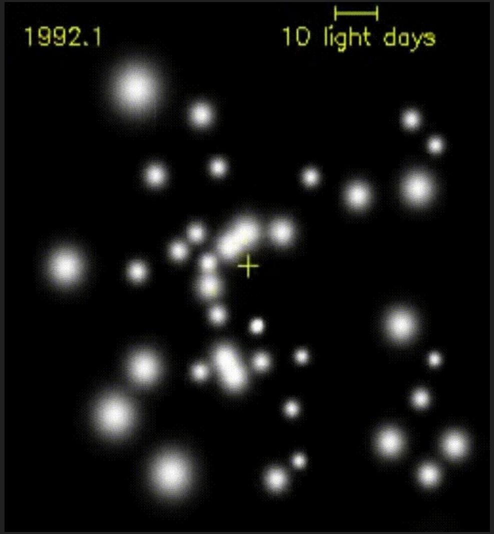
Our Galactic Centre



13 year time lapse of stars around Sgr A* (ESO)

- **Estimate** the **mass** of our SMBH by following paths of surrounding stars and using Kepler's law.
- Provides **indirect evidence** for a ~3 million solar mass black hole.
- We are waiting for a **direct image** from the Event Horizon Telescope.

Our Galactic Centre



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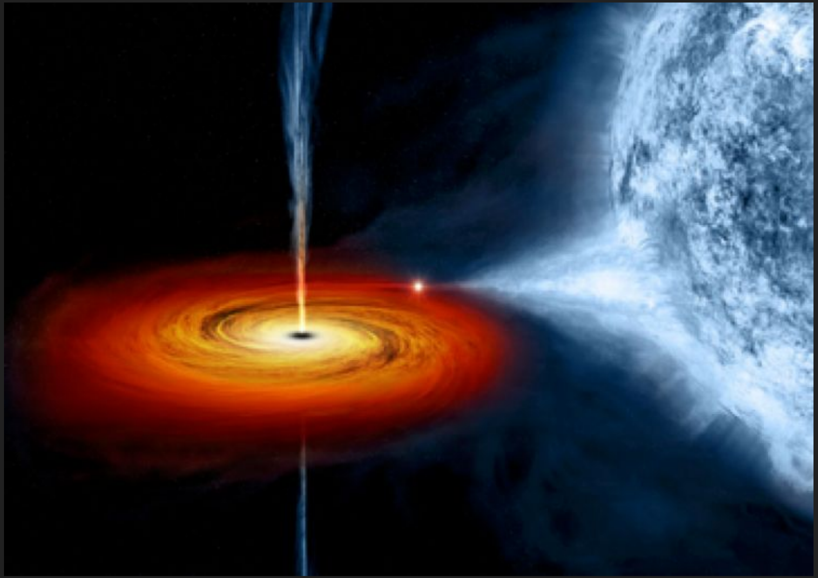
Compact Binaries



Close Binaries

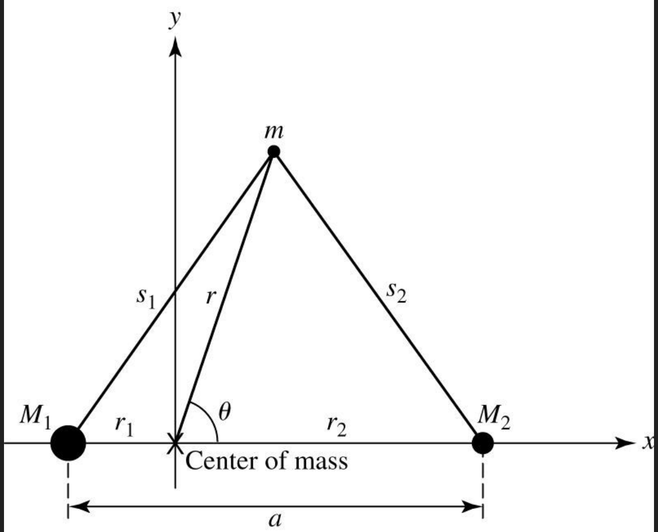
- A large fraction of stars are not isolated but **systems of multiple objects**. The majority are far apart and do not influence each other.

- If two stars in a binary are **close enough**, orbital and rotational energy is dissipated by tidal interactions until the **system rotates rigidly** (same sides keep facing each other).

Corotating Coordinates

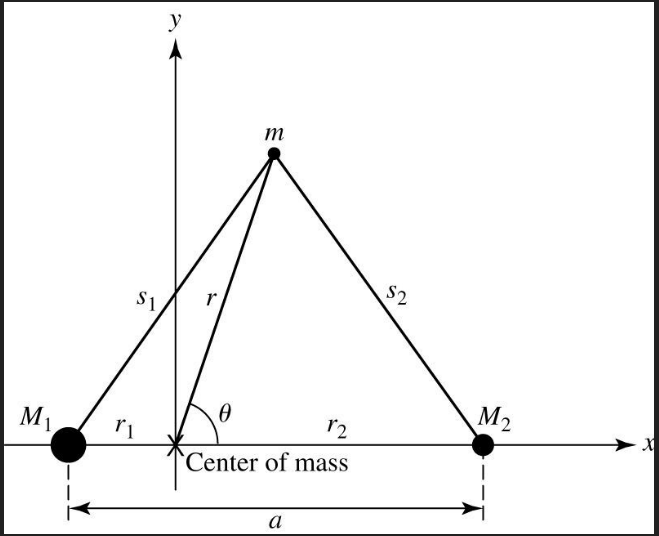
- Consider a **corotating coordinate system** following the stars about their centre of mass.

- In the **rotating frame**, both stars are at rest and the **gravitational attraction** is balanced by a **centrifugal force**.



Gravity in Close Binaries

- The **effective potential energy** for a small **test mass** m, located in the orbital plane is



$$U = -G\left(\frac{M_1 m}{s_1} + \frac{M_2 m}{s_2}\right) - \frac{1}{2} m\omega^2 r^2.$$

- Corresponding effective gravitational **potential**:

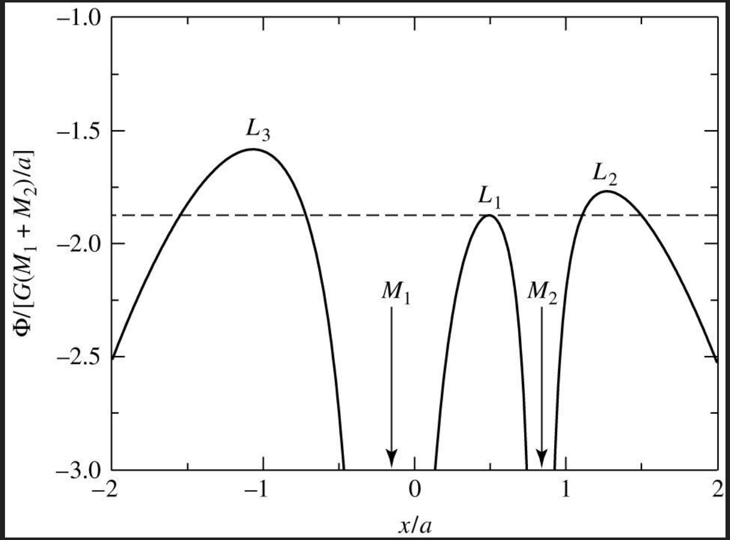
$$\Phi = -G\left(\frac{M_1}{s_1} + \frac{M_2}{s_2}\right) - \frac{1}{2}\omega^2 r^2.$$

Lagrange Points

- Use the **geometry** to determine Φ at any point in the orbital plane. Force on m in x-direction is

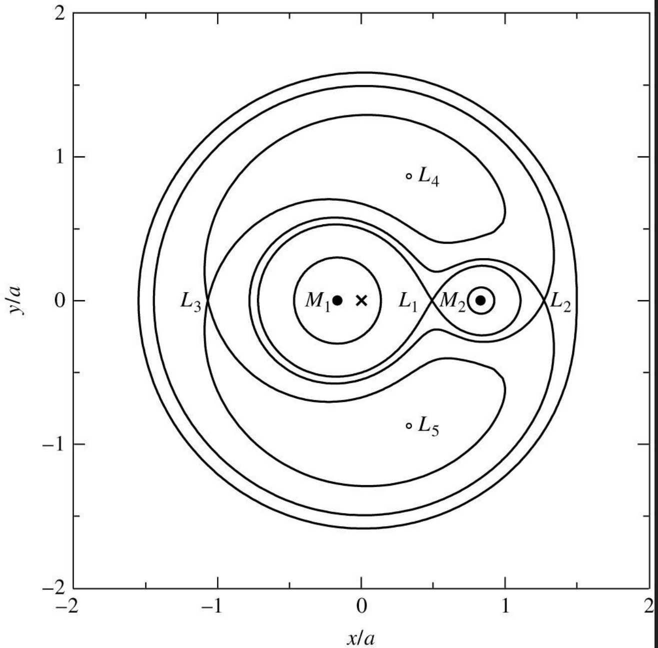
$$F_x = -\frac{dU}{dx} = -m\,\frac{d\Phi}{dx}$$

- At the **Lagrange points** L1, L2 and L3, the force on m vanishes. Points are **unstable** equilibria.



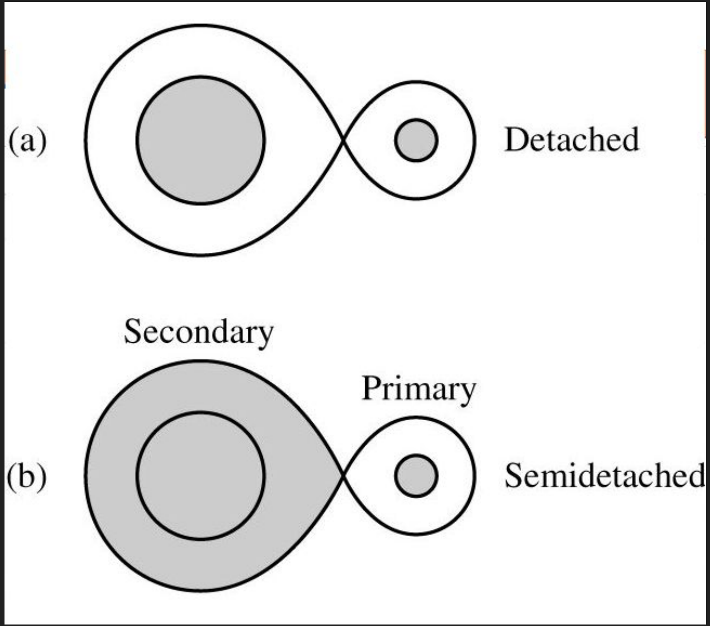
Equipotential Surfaces

- Plot points in space that have the same Φ values (**equipotential surfaces**).

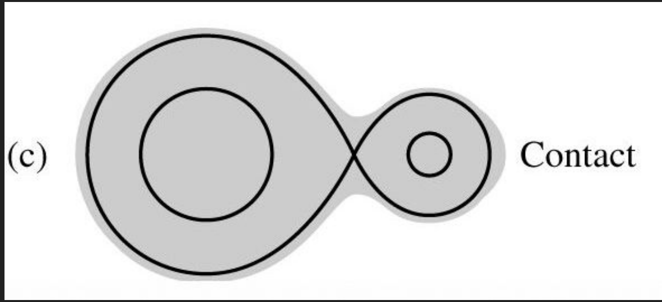


- Expanding stars fill regions of **successively larger Φ**.
- Region through L1 is called **Roche lobe**. Mass transfer in binaries occurs at L1.

Binary Classification

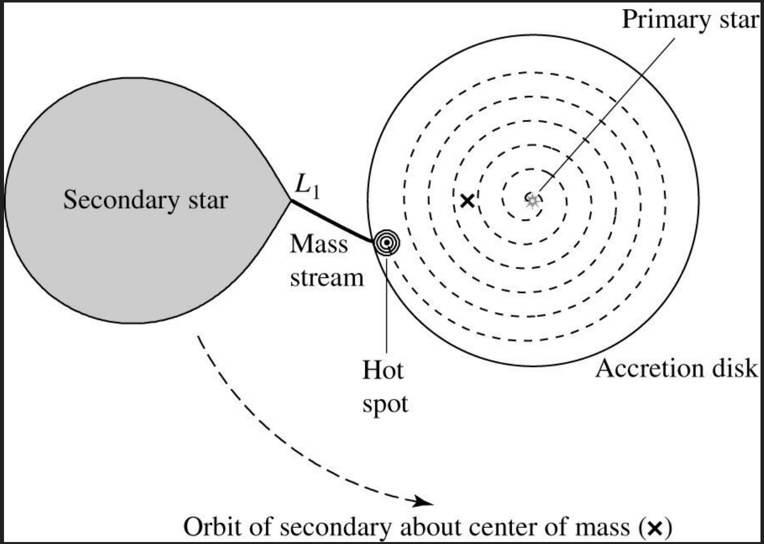


- **Appearance** of a binary depends on which equipotential surfaces are filled.



Accretion Disks

- **Orbital motion** keeps matter from falling directly onto star but leads to formation of a **thin disk**.



- **Viscosity** (internal friction in the gas) converts kinetic energy (*somehow*) into thermal radiation, leading to **energy loss**. Gas **spirals** slowly towards the primary.

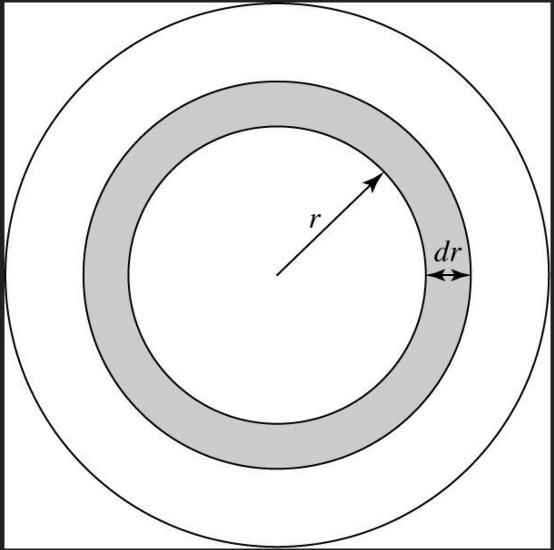
Disk Luminosity I

- An **optically thick** disk emits like a black body of local temperature T at each radial distance r.
- Neglect radial inward motion (and thus viscous disk processes) and assume that disk mass is much smaller than primary's mass.
- Orbiting gas of mass m has **total energy** (from Virial theorem):

$$E = -G\,\frac{M_1 m}{2r}.$$

Disk Luminosity II

- As the gas spirals inward it loses energy, which causes T and powers its black body radiation.
- Consider a **ring** of mass m.
- In the **steady state** no mass builds up in the ring, so that a mass t·dM/dt has to pass it.



Disk Luminosity III

- **Energy conservation** dictates that radiated energy is equal to energy passing through ring:

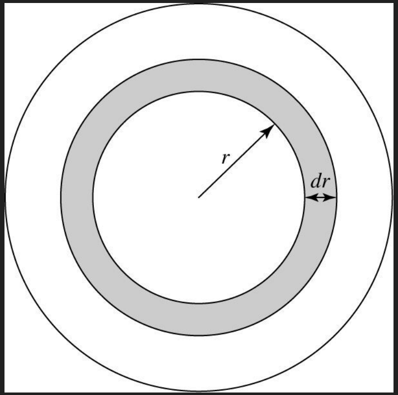
$$dE = \frac{dE}{dr}dr = \frac{d}{dr}\left(-G\frac{M_1 m}{2r}\right)dr = G\frac{M_1\dot{M}t}{2r^2}dr,$$

- The corresponding **luminosity** of the ring is

$$dL_{\mathrm{ring}}t = dE = G\frac{M_1\dot{M}t}{2r^2}dr.$$

Disk Luminosity IV

- The **surface area** of the ring (considering top and bottom) is



$$A = 2(2\pi r\, dr)$$

- Using the **Stefan-Boltzmann law** gives

$$dL_{\text{ring}} = 4\pi r \sigma T^4\, dr = G\frac{M_1 \dot{M}}{2r^2}\, dr$$

σ is the Stefan-Botzmann constant.

Disk Luminosity V

- Solving for the **disk temperature T** gives

$$T = \left(\frac{GM\dot{M}}{8\pi\sigma R^3}\right)^{1/4}\left(\frac{R}{r}\right)^{3/4}$$

M, R are mass and radius of the primary star.

- **Integrating** the equation from r=R to r=∞ gives finally for the **accretion disk luminosity**

dM/dt is mass accretion rate due to the secondary.

$$L_{\text{disk}} = G\frac{M\dot{M}}{2R}.$$

Disk Luminosity VI

- In **absence of a disk**, the accretion luminosity (rate at which kinetic energy is given to star) is

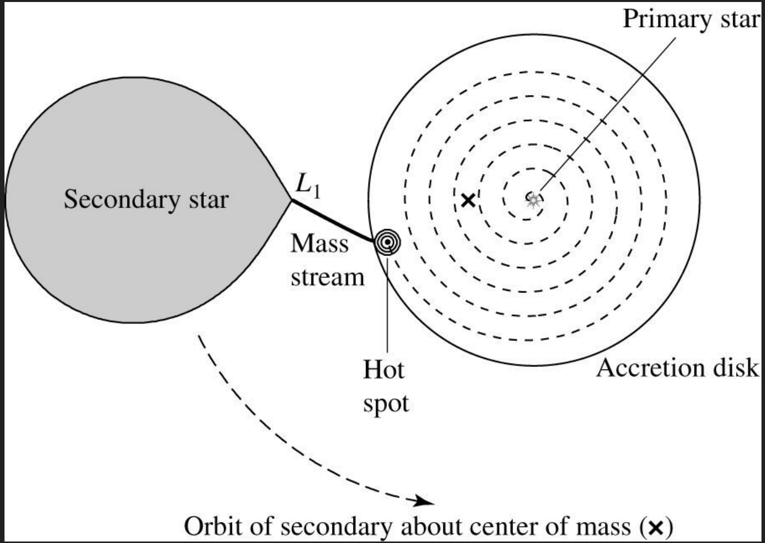
$$L_{acc} = G\,\frac{M\dot{M}}{R}$$

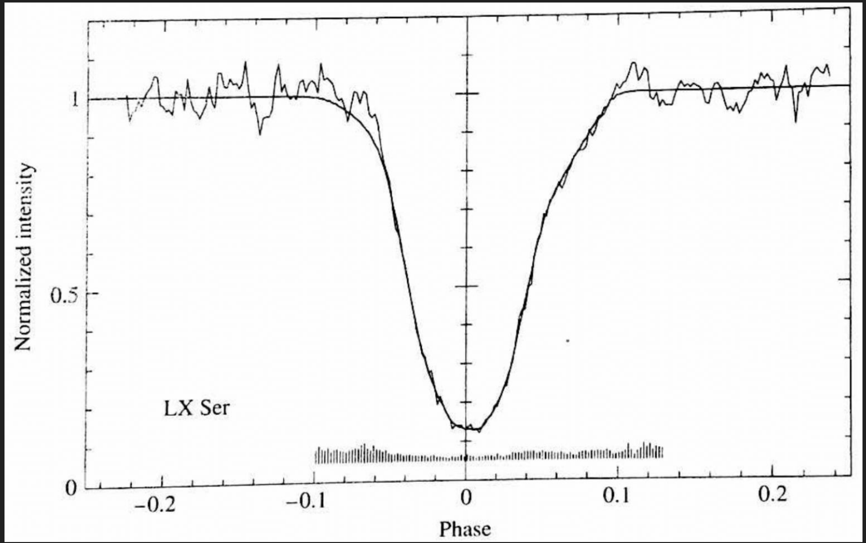
Used to calculate Eddington luminosity.

- **Half** of the available **energy budget** is radiated by the disk, the **other half** will be deposited on the **surface** of the star (or in boundary layer).

Observational Evidence

- Light curves from **eclipsing, semi-detached** binaries provide evidence that picture is correct.





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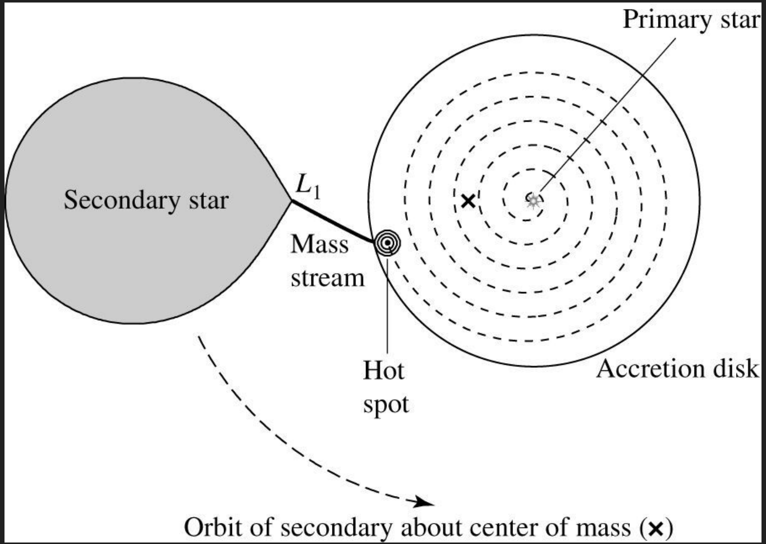
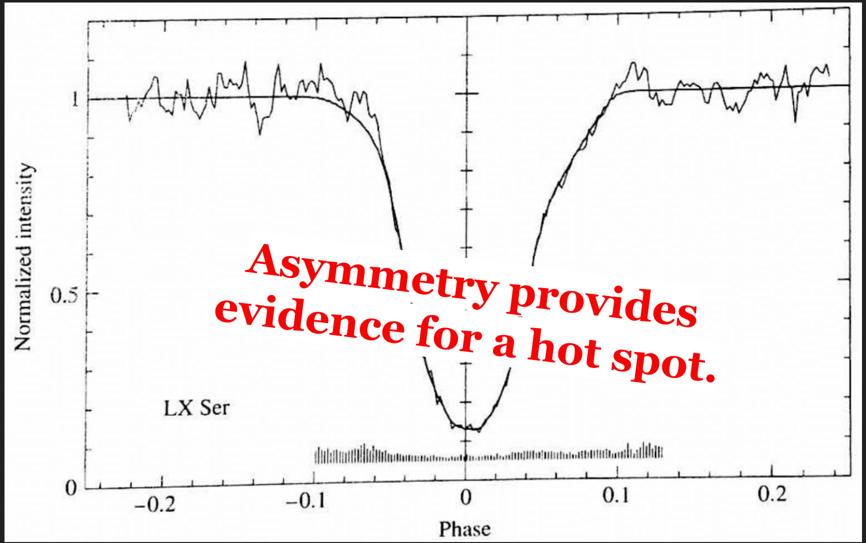


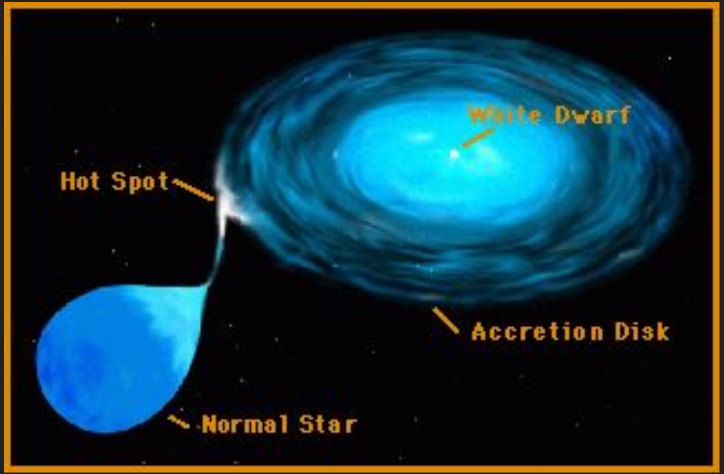


Different Kinds of Binaries

- Close binaries can evolve in very different ways depending on masses and separation forming e.g.
  - **Cataclysmic variables** (CVs)
  - **X-ray binaries**
  - **Double** (merging) **compact binaries**

Cataclysmic Variables I

- CVs are systems with short orbital periods (typically hours) where a **White Dwarf** (primary) is combined with a cool **normal star** (secondary).

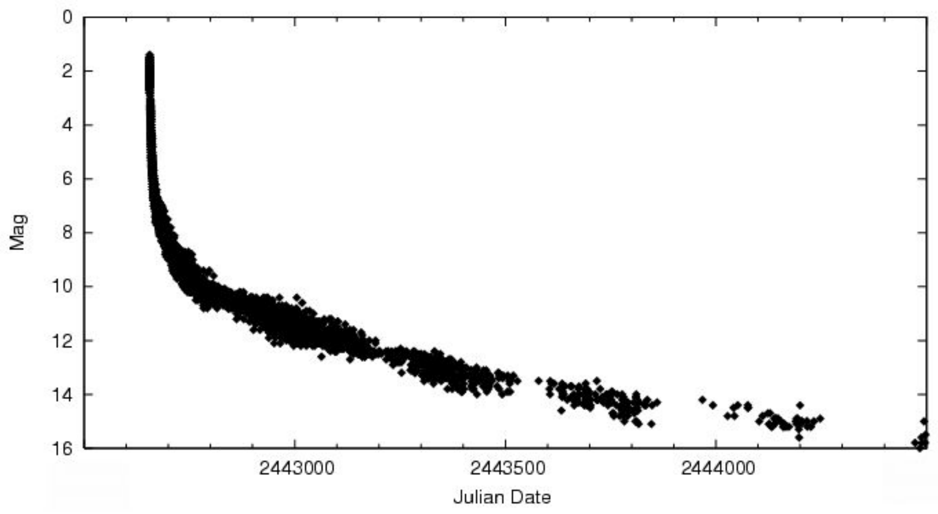


- The **donor star** fills its Roche lobe and mass is transferred to WD via accretion disk.

Cataclysmic Variables II

- CVs show **irregular outbursts** alternating with quiescent states. Bursts are bright enough to be seen by eye - alternative name: **classical novae**.
- Outbursts occur when density/temperature of material accumulating on the WD surface exceeds the **threshold** for **hydrogen fusion** reactions.

Cataclysmic Variables III



Nova Cygni 1975
(AAVSO)

- Once burning layer is ejected and **fuel gone**, WD can cool. The whole process eventually restarts.

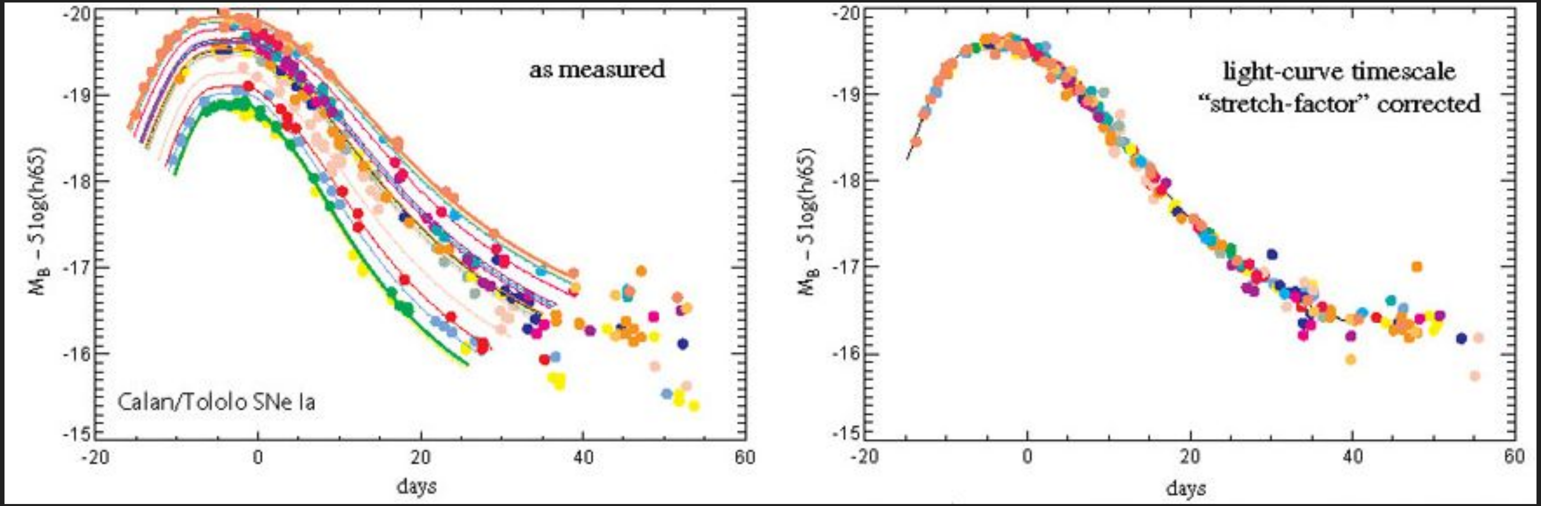
Type-Ia Supernovae I

- If accretion lasts long enough to bring WD to the **Chandrasekhar limit**, runaway carbon fusion can be ignited, triggering a **type-Ia supernova**.
- Due to the characteristic mass limit, the explosion mechanism is **very uniform**, leading to very **similar peak luminosities**.

Type-Ia Supernovae II

- Due to stability, type-Ia supernovae are used as **standard candles** to measure distances to host galaxies (luminosity mainly depends on distance).

Kim et al. (1997)



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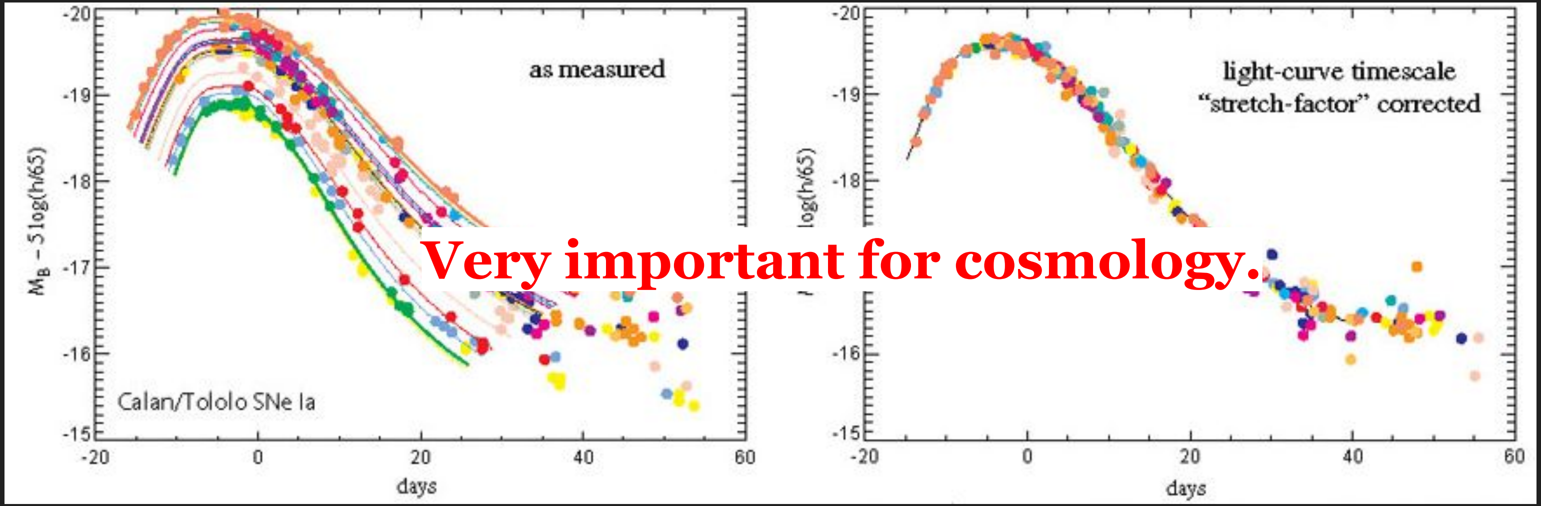


Very important for cosmology.

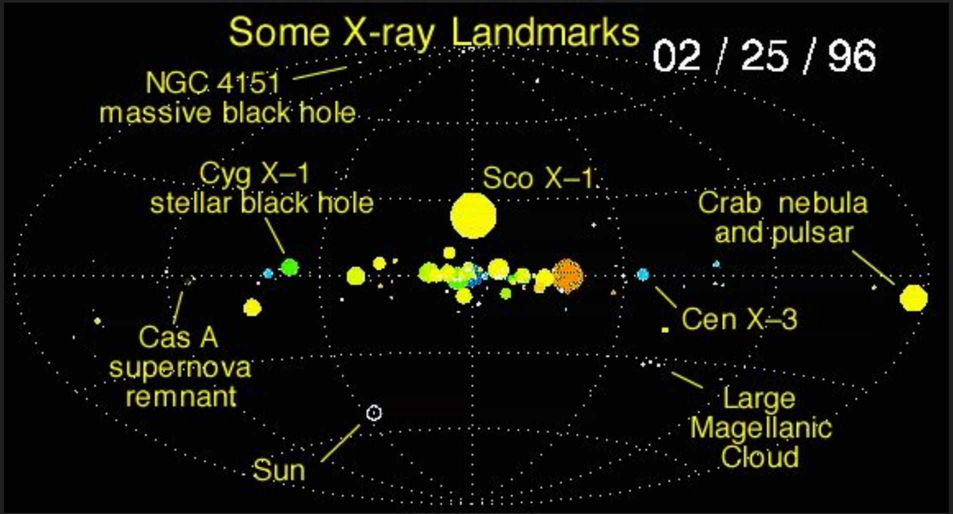
Kim et al. (1997)

X-ray Binaries

- If one of the binary stars is sufficiently massive to explode in **core-collapse SN**, a NS or BH forms.
- If the system survives the explosion, the compact object accretes matter from its companion.
- **Deep gravitational potential** causes strong gas acceleration and strong **X-ray emission**.

Scorpius X-1

- Sco X-1 is a binary X-ray pulsar and the second strongest X-ray source in the sky.



X-ray sky (NASA)

Scorpius X-1

The sun is the brightest X-ray source.

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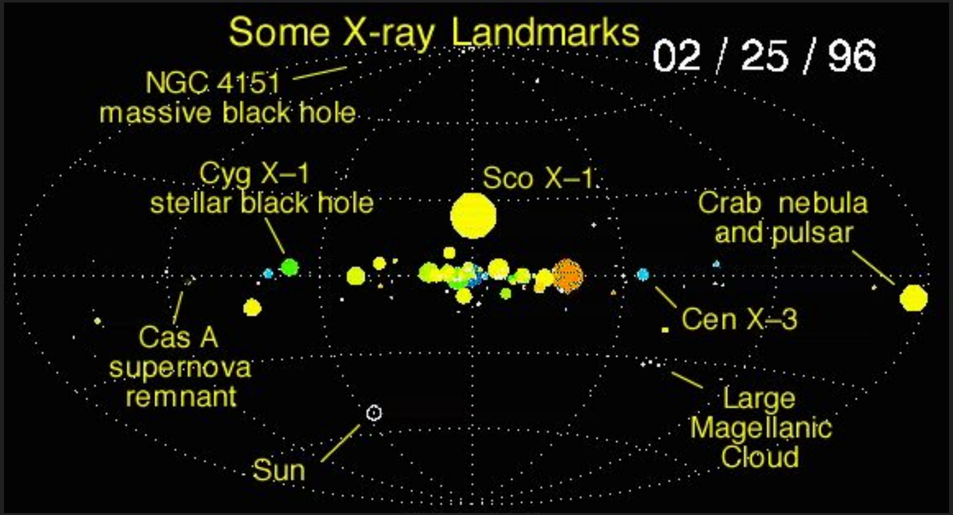


- It was the first **extrasolar source** detected.
- Radio pulsations are very weak.

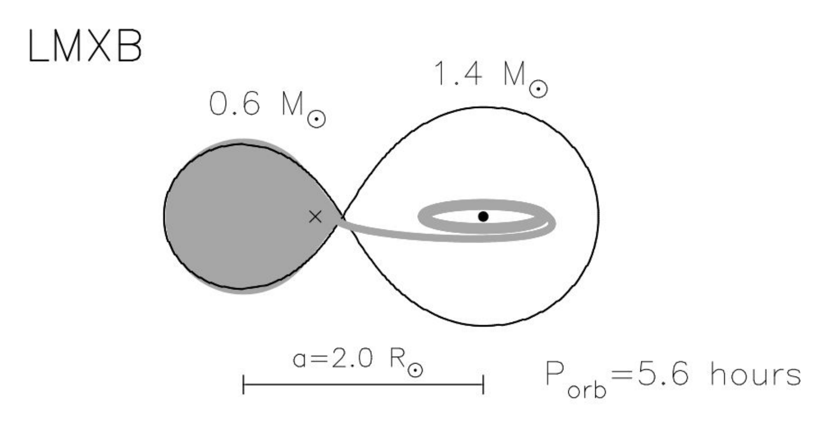
X-ray sky (NASA)

Low-Mass X-ray Binaries I

- Donor is **less massive** than the compact object.

- Compact object accretes from its companion via **disk accretion**, causing strong X-ray but little optical emission.

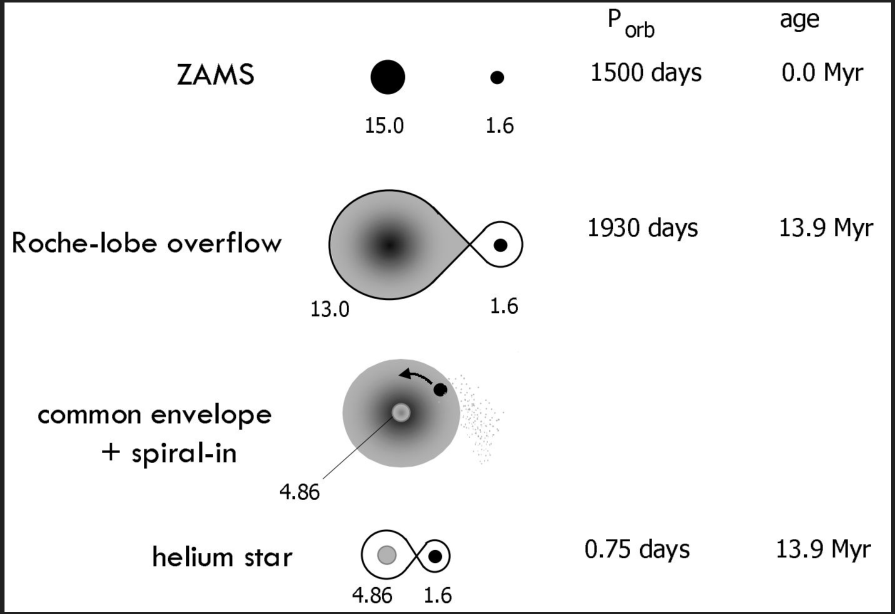
LMXBs are very compact with short orbital periods.

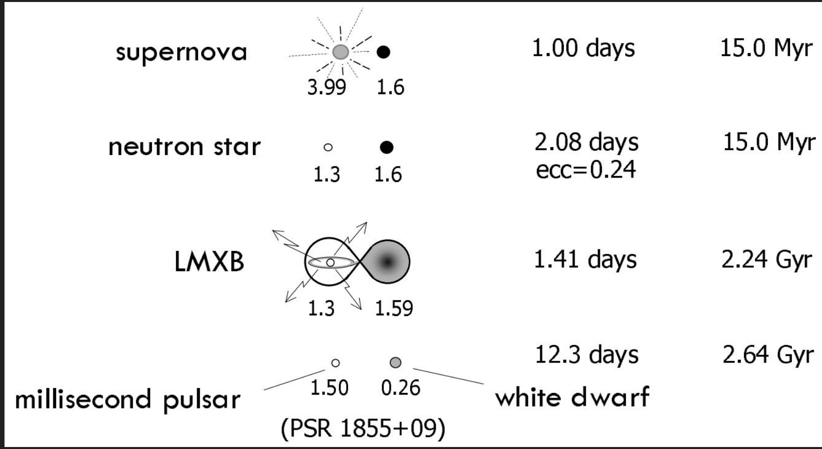


Tauris & van den Heuvel (2003)

Low-Mass X-ray Binaries II

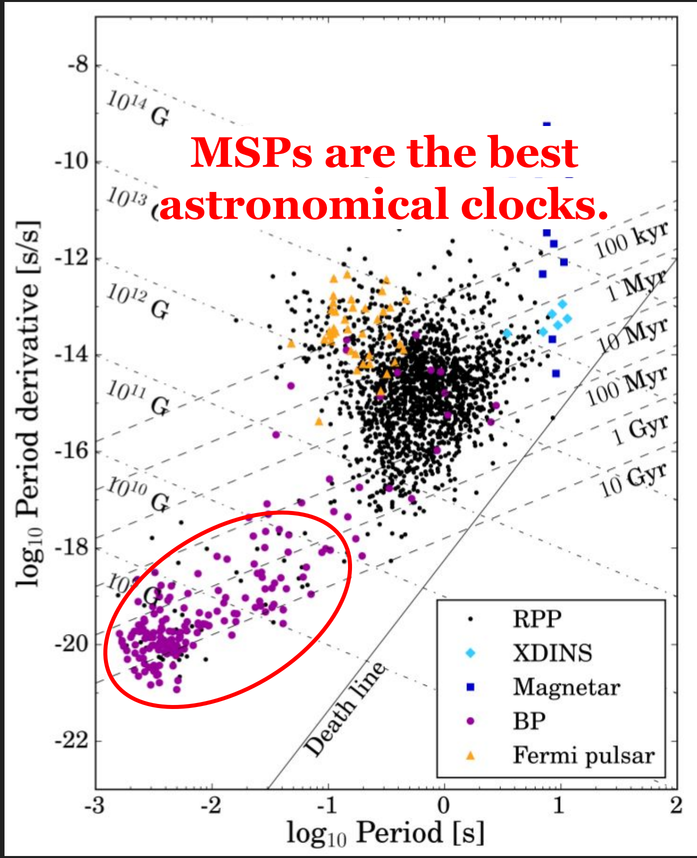
- LMXBs formation involves an **asymmetric SN**.





Tauris & van den Heuvel (2003)

Millisecond Pulsars

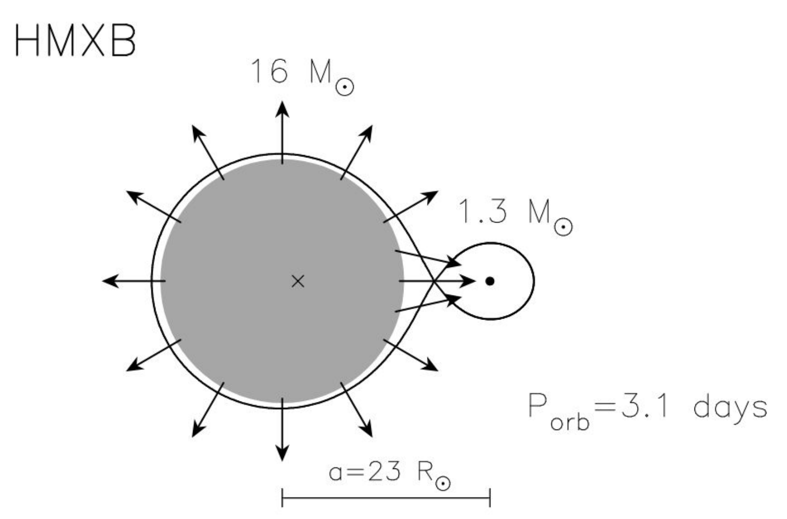


- MSPs have periods between **1-10ms** (located in the lower left of P-Pdot diagram).
- MSPs are **old and recycled** objects, spun up by **accreting matter** (angular momentum) from a companion (in LMXB).

High-Mass X-ray Binaries I

- Donor is a very **massive star**, usually easily detected in the optical.
- Compact object accretes matter from the **stellar wind** of its companion, causing X-ray emission.

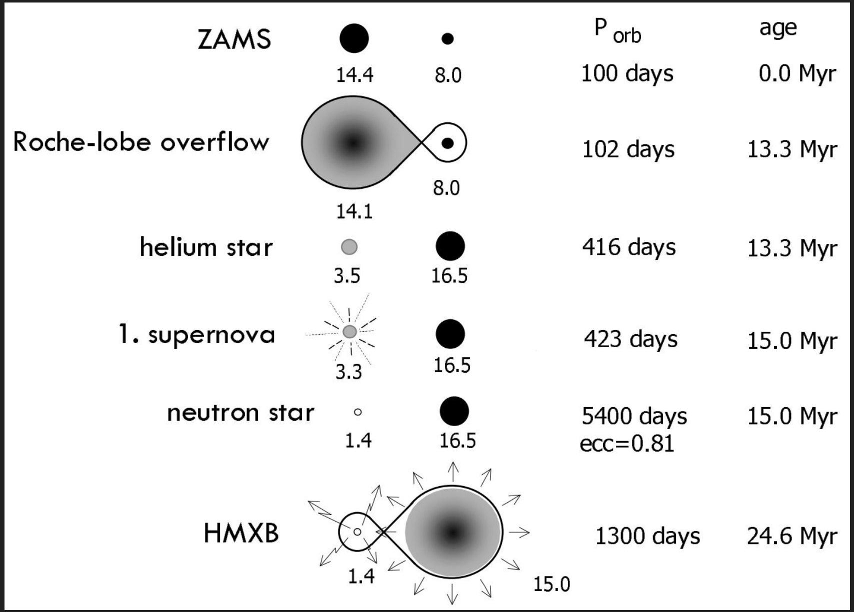
Cyg X-1 is a HMXB.

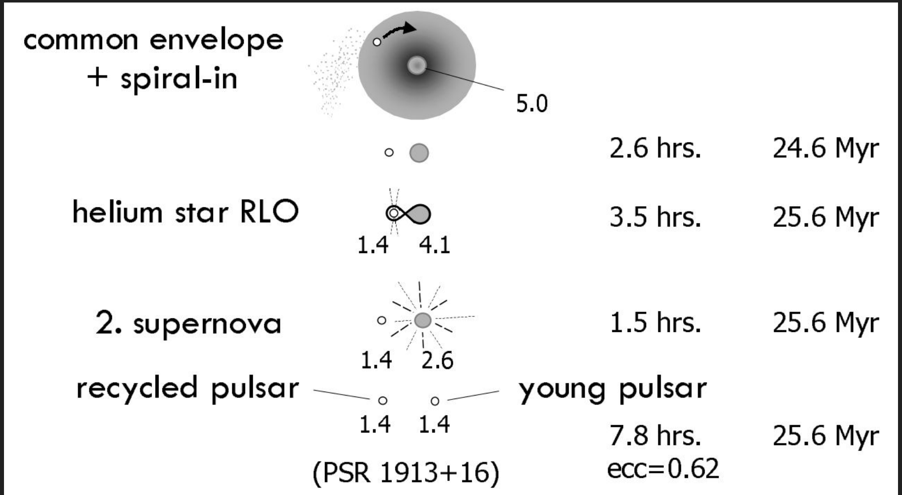


Tauris & van den Heuvel (2003)

High-Mass X-ray Binaries II

- HMXBs from two massive stars, leading to **2 SN**.

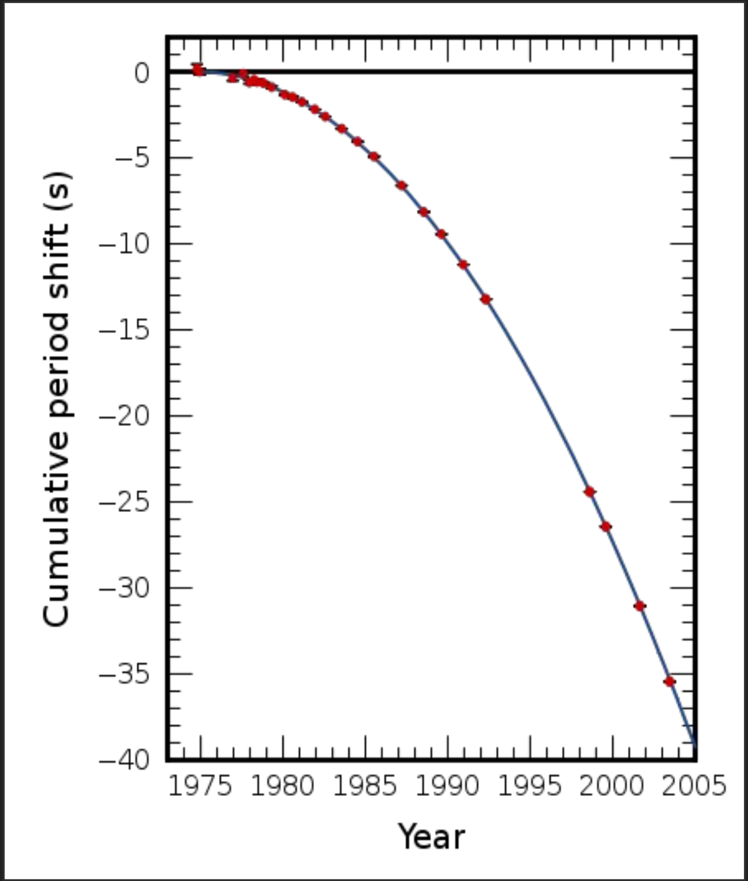




Tauris & van den Heuvel (2003)

Double NS Binaries

- Double NS systems are highly relativistic systems, making them **excellent laboratories** to test **GR**.
- Hulse-Taylor pulsar (PSR B1913+16) provided first **indirect** detection of GWs.



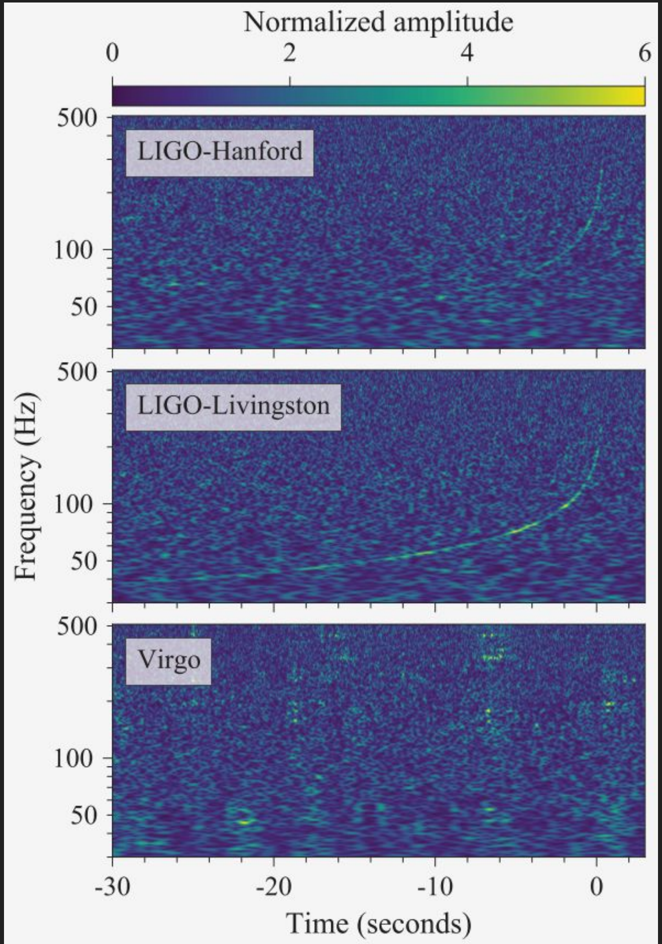
Weisberg & Taylor (2004)

GW Detection

- First **direct detection** from two merging NSs was made last year by LIGO - GW170817.

- Source was localised due to **counterparts** in γ-ray, X-ray, radio, optical and IR.

- **Multi-messenger** astronomy!!



Abbott et al. (2017)