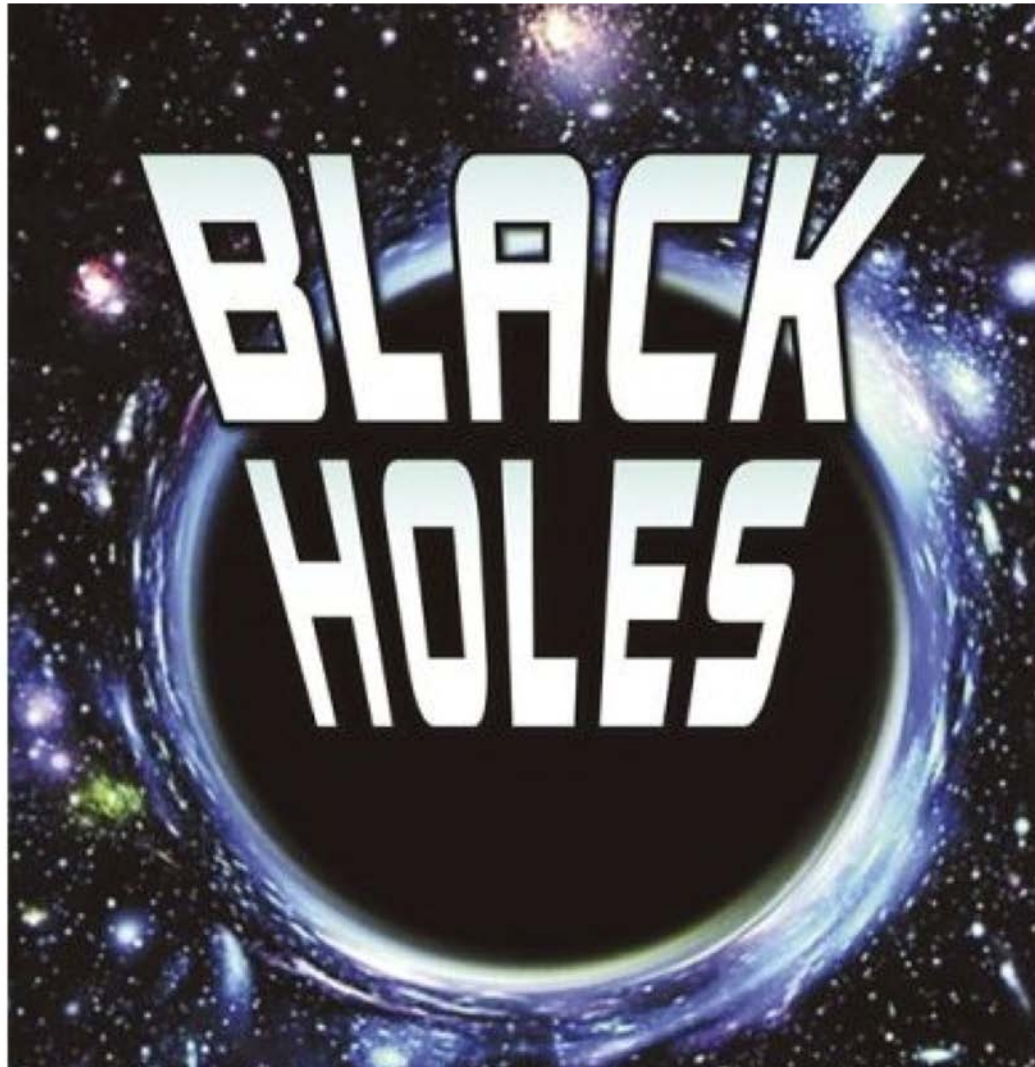


Black Holes in Our Backyard



Black Holes in Our Backyard

How does one find a black hole?

Method proposed by Zeldovich :

- Look for a binary system containing a normal star and an X-ray emitting companion.

By applying Newton's law to the orbital properties (measured speed and orbital period) one can infer the mass of the black hole or at least place a lower limit on its mass.

X-ray observations of binaries provided the first strong evidence for the presence of black holes.

Black Holes in Our Backyard



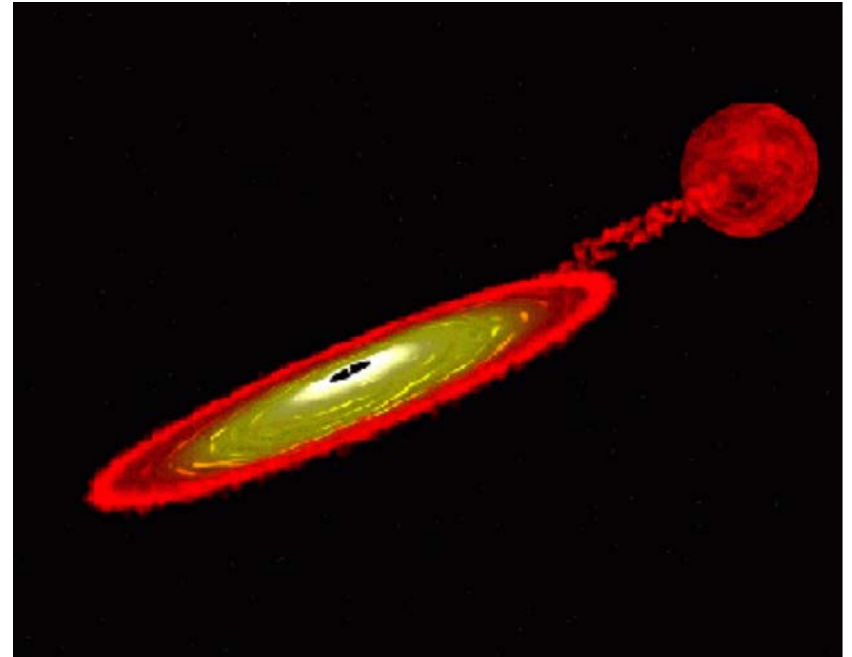
The first glimpse of the X-ray sky came from sounding rockets equipped with X-ray detectors. (picture: Final Prelaunch Tests of an Aerobee sounding rocket.)

In 1962 such a mission lead by R. Giacconi discovered a bright X-ray source near the constellation Scorpius. It was thus named SCO -X1.

SCO-X1: The First Extrasolar X-ray Source Discovered

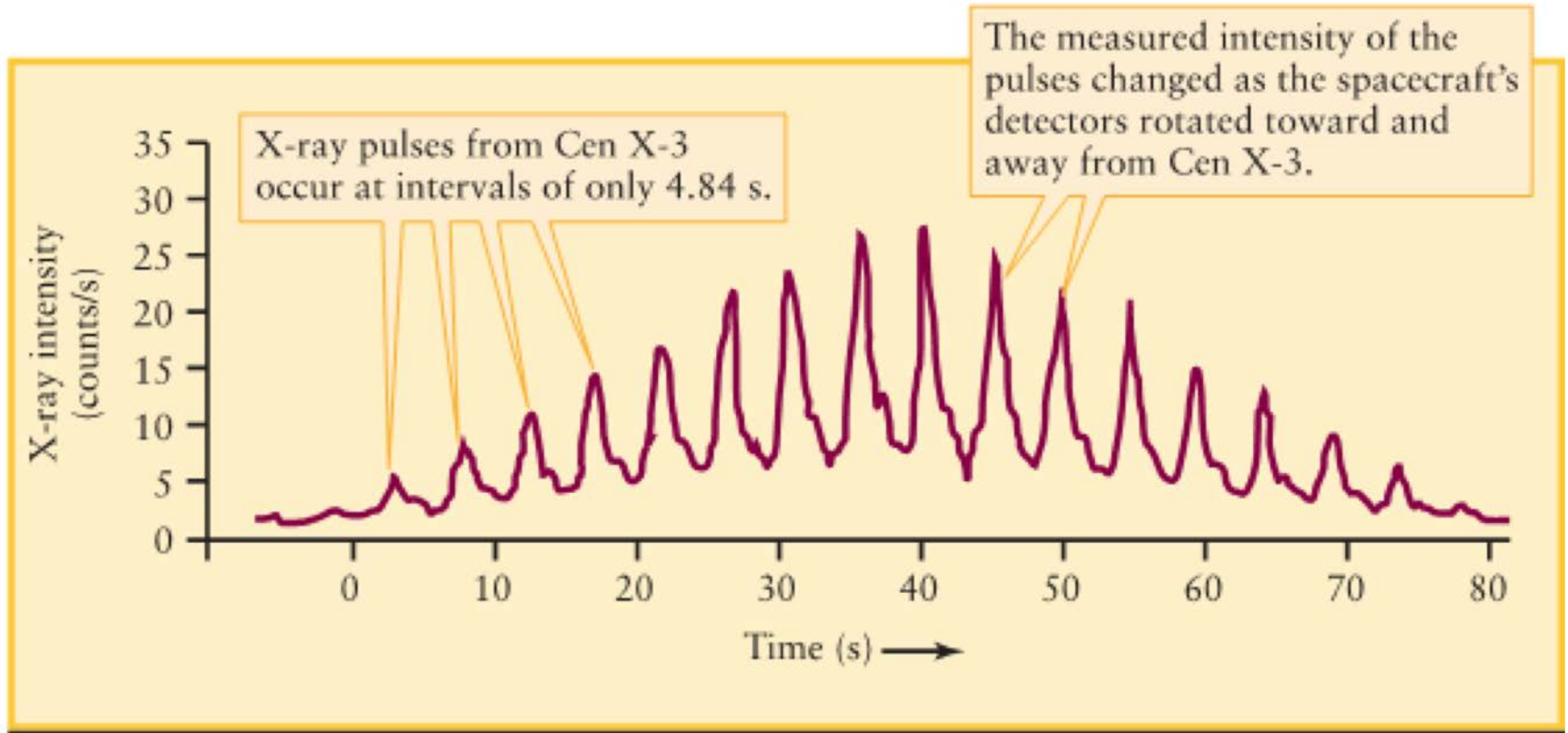
We now know that **SCO -X1** contains a **neutron star** orbiting a normal star and the X-rays come from accretion of material from the normal star onto the neutron star.

This mission also discovered a diffuse source of X-ray emission referred to as the X-ray background. It turns out that most of the **diffuse X-ray background** comes from **black holes**.



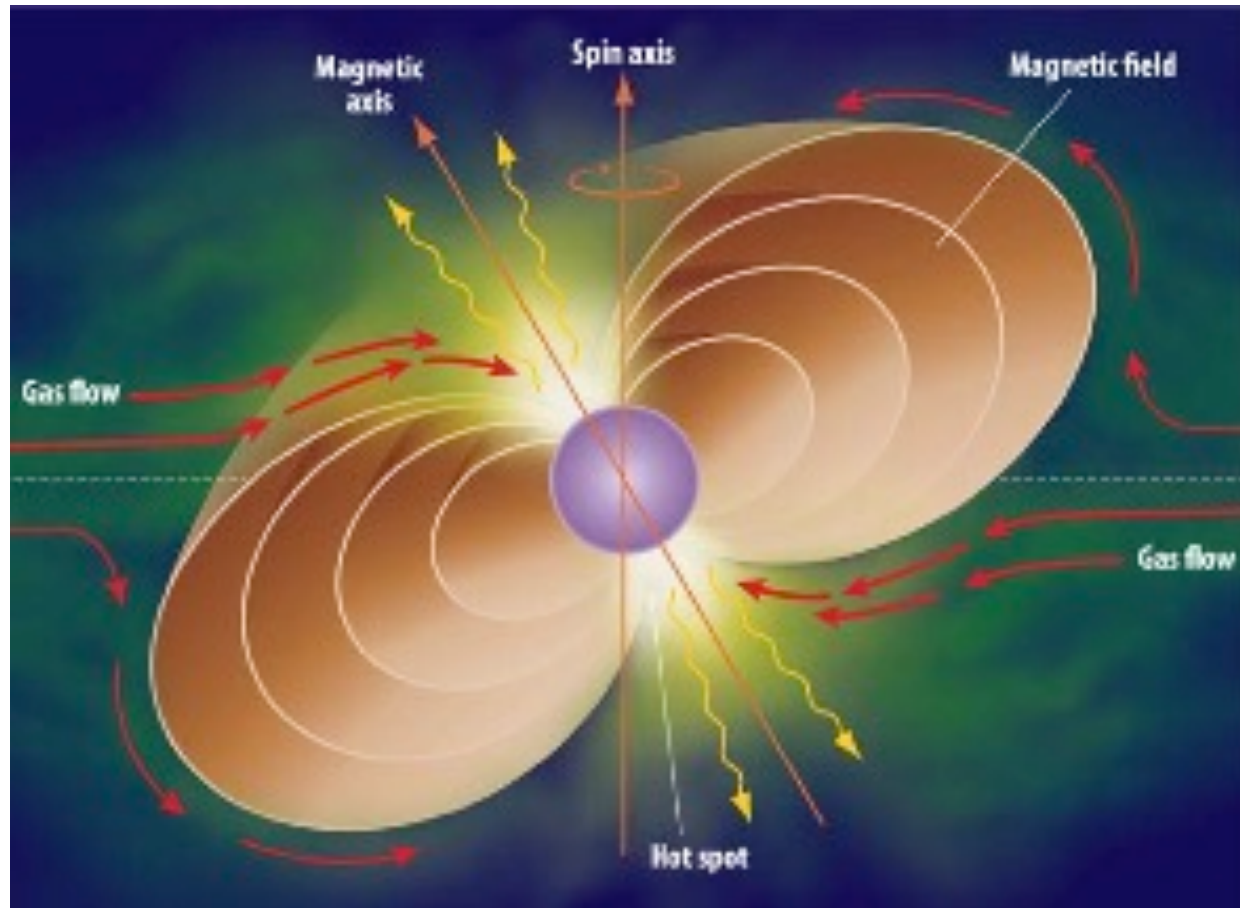
Low Mass X-ray Binary (the companion star has a mass that is similar to or less than that of our Sun)

X-ray Binary Pulsars



X-ray pulses from Centaurus X-3. Centaurus X-3 is a neutron star in a binary system.

X-ray Binary Pulsars

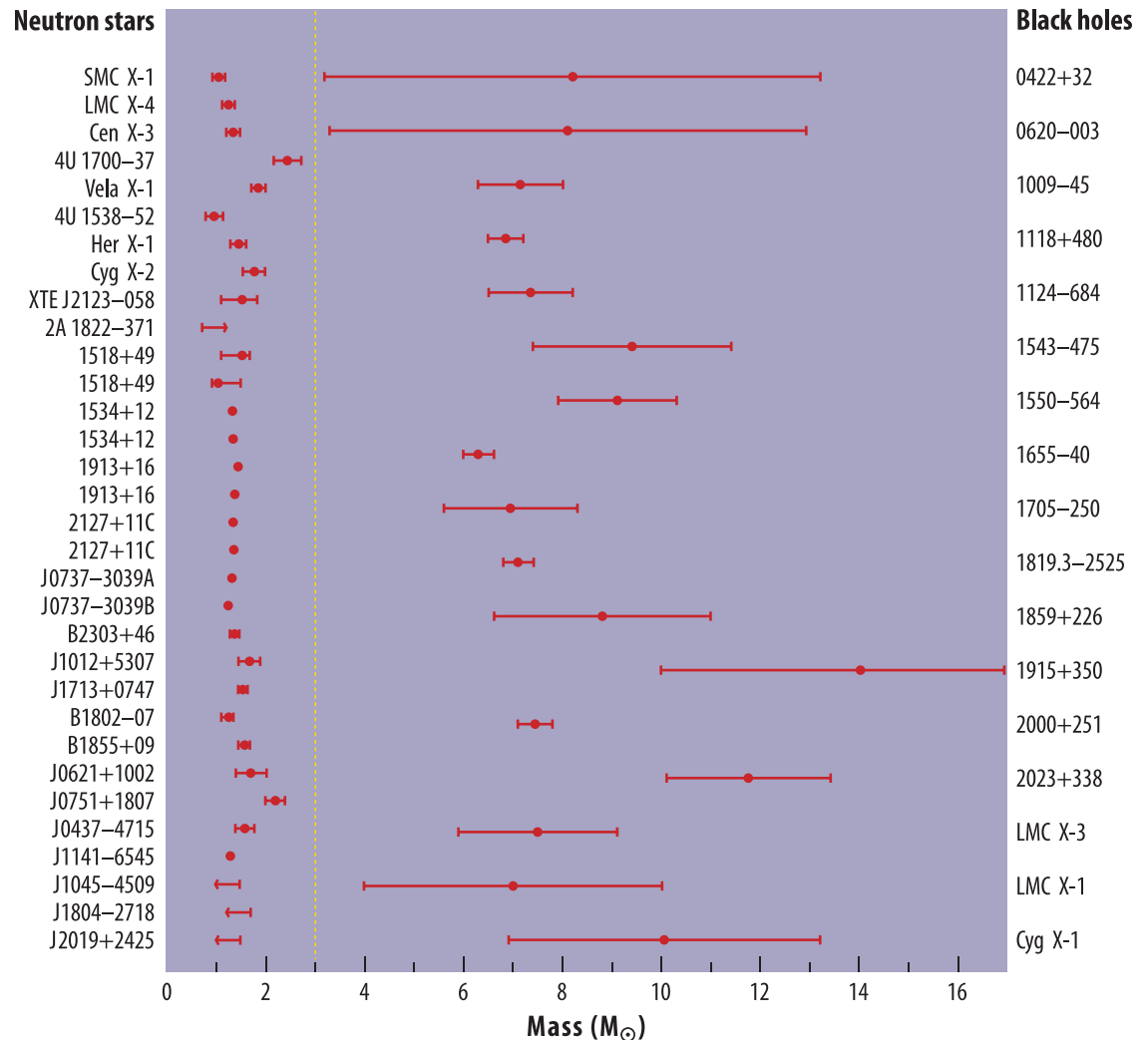


In an X-ray binary pulsar, gas from a companion star is funneled to the magnetic poles of the neutron star, forming hot spots that emit X-rays rather than radio waves.

Masses of Neutron Stars and Black Holes in Binaries

The diagram shows masses of the compact objects in binaries as estimated using Kepler's modified 3rd law.

The compact objects left of the vertical dashed line are thought to be neutron stars and those to the right black holes.

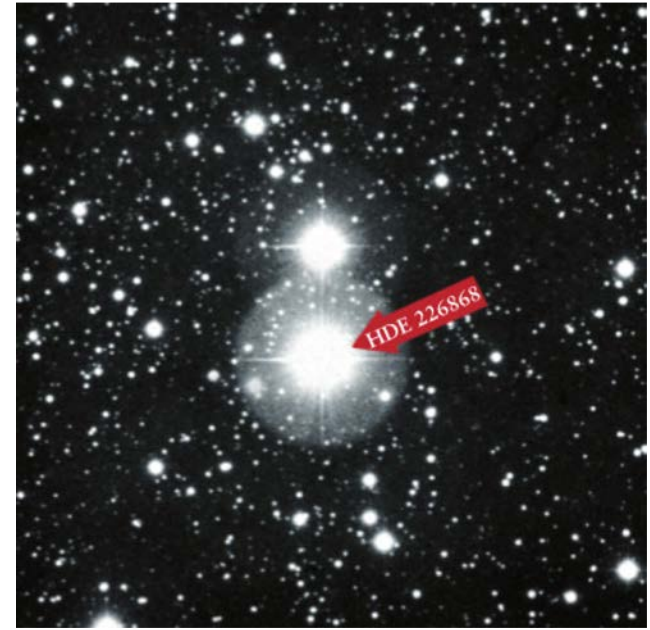


Black Hole Candidates

Cygnus X-1 is thought to be a black hole in a binary system with a companion supergiant B0 star. The X-ray emission of Cygnus X-1 changes significantly within 0.01 sec. This places a limit on the size of the object.

The shortest variation time in the flux of an object of size D is the time that light takes to travel across the object (t_{lc}).

$$\begin{aligned} t_{\text{variation}} > t_{lc} &= D/c \rightarrow D < ct_{\text{variation}} \rightarrow \\ \rightarrow D &< 3 \times 10^5 \text{ km/sec} \times 0.01 \text{ sec} \\ \rightarrow D &< 3,000 \text{ km} \end{aligned}$$



HDE 226868 is a B0 star with an estimated mass of $30 M_{\odot}$ and the other object in the binary is estimated to have a mass of $\sim 10 \pm 3 M_{\odot}$ implying that it is a black hole.

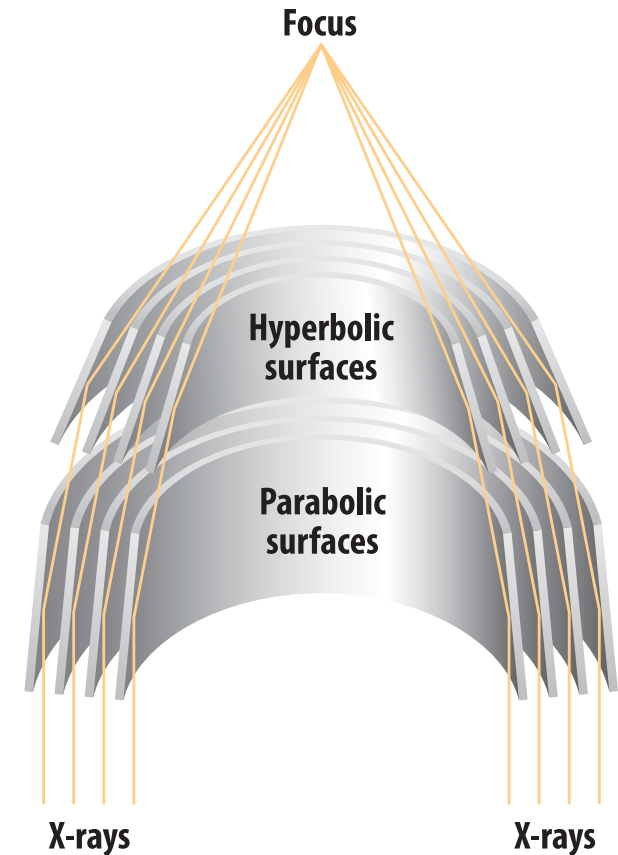
Detecting X-rays from Black Hole Candidates

Black Holes in binary systems are often discovered from their X-ray emission.

The detection of X-rays from binaries was first made in the 60s with X-ray detectors on **sounding rockets** and beginning in the 70s with the deployment **X-ray satellites**.

X-rays cannot be focused by conventional mirrors like those used in optical telescopes. In X-ray telescopes the X-rays are focused into an image by reflecting off the insides of tapered metallic tubes at shallow angles.

To achieve a large collecting area many nested mirrors are often used.





Accretion

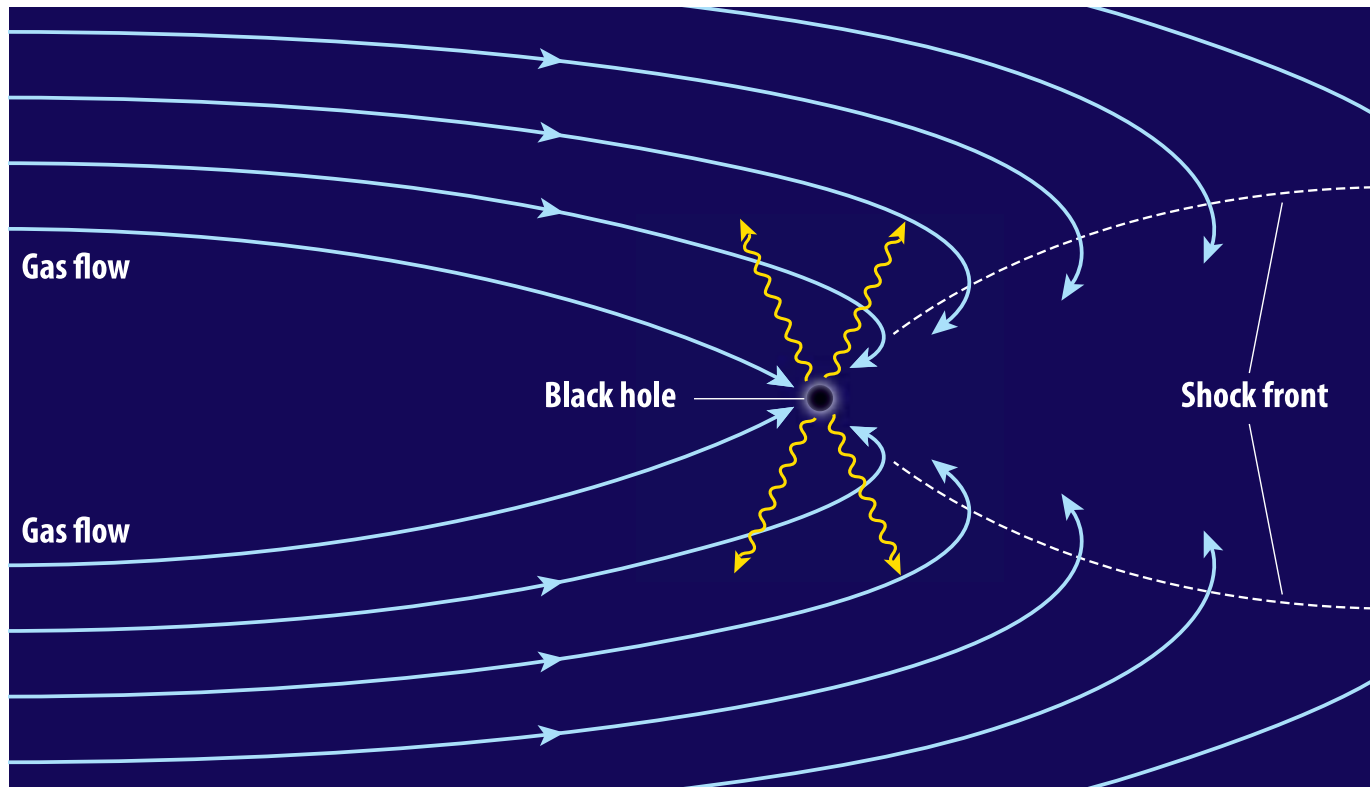
The infall of matter onto a gravitating object is called **accretion**.

For a non-gravitating sphere the rate of accretion of gas onto an object depends on the **area** of the object and the **speed** and **density** of the accreting particles.

For a gravitating sphere the rate of accretion would also depend on the **mass** of the object.

Bondi-Hoyle-Lyttleton theory describes accretion by a gravitating object moving through a gas.

Accretion



This diagram shows how accretion can occur onto a black hole moving through diffuse gas. The black hole's gravity causes the flow to converge and a shock front forms “downstream”. The shocked gas loses energy and can fall into the black hole.

Accretion

If the kinetic energy of a mass m in the vicinity of the compact object is less than its potential energy then it will be accreted.

According to Bondi theory the **accreted mass per unit time** is:

$$\text{Accretion Rate} = \pi r_{eff}^2 \rho v,$$

where ρ is the density of the gas, v is the velocity of the gas and r_{eff} is the effective radius



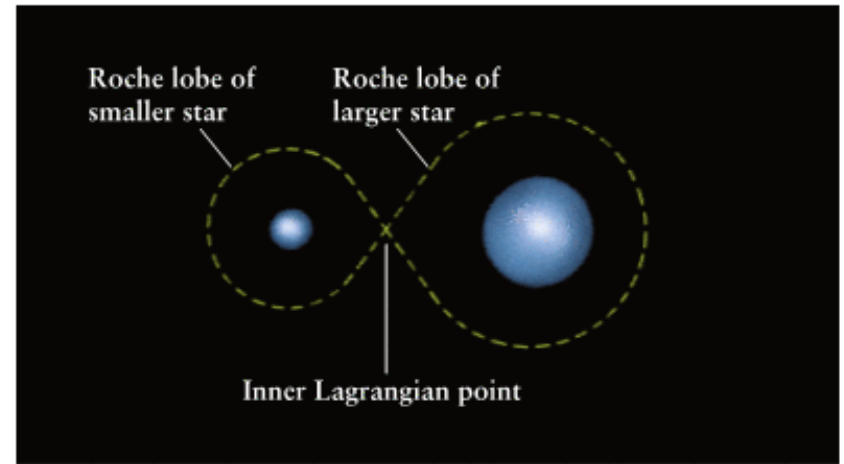
BONDI

Accretion in Binary Systems

A red giant in a close binary system may **transfer mass** to its companion star and alter the evolution of both stars.

Roche lobe: A teardrop-shaped volume surrounding a star in a binary inside which gases are gravitationally bound to that star.

If gas from the outer layers of a red giant moves beyond its Roche lobe it is not bound and may be transferred to the companion star.

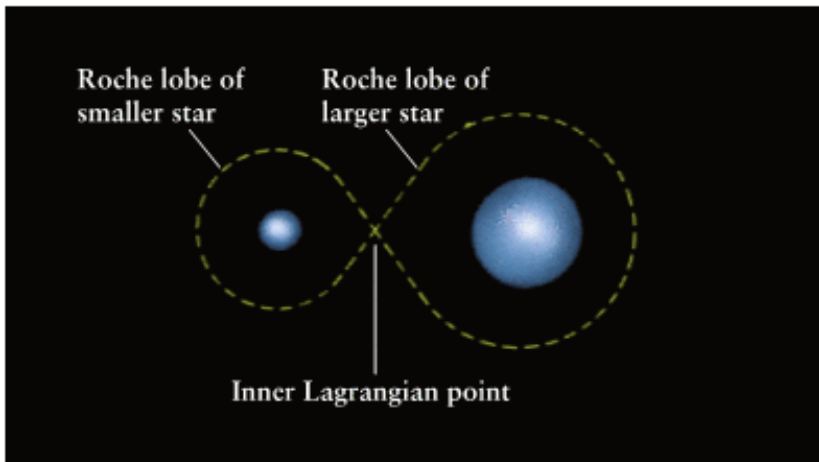


(a) Detached binary: Neither star fills its Roche lobe.

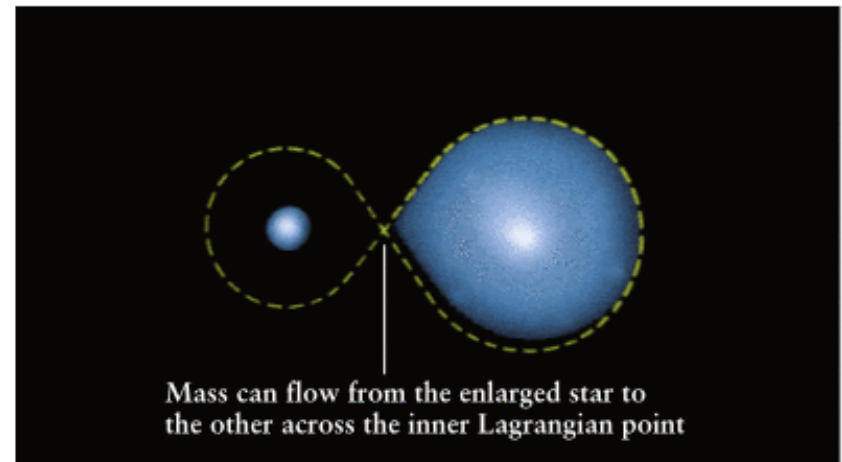
The point where the two Roche lobes touch is called the **inner Lagrangian point**.

If a star does not fill its Roche lobe it is called **detached**.

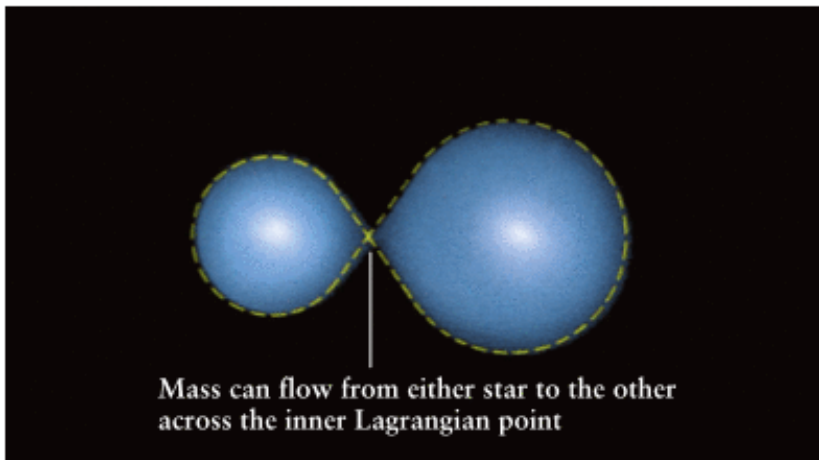
Accretion in Binary Systems



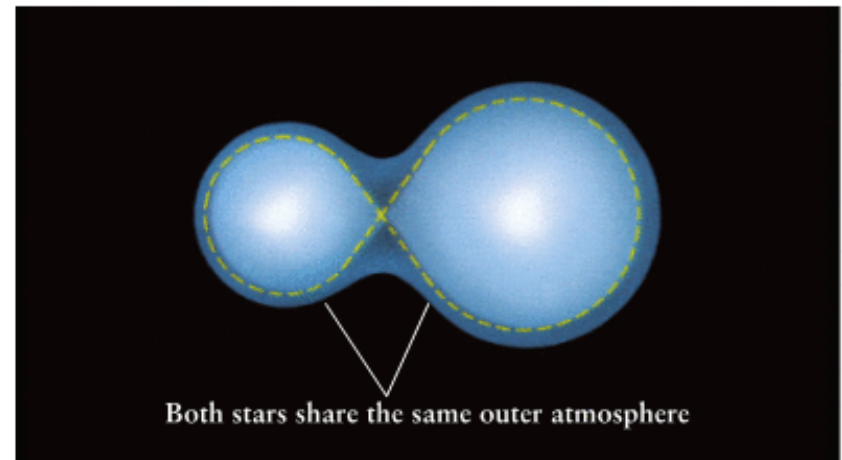
(a) Detached binary: Neither star fills its Roche lobe.



(b) Semi-detached binary: One star fills its Roche lobe.



(c) Contact binary: Both stars fill their Roche lobes.



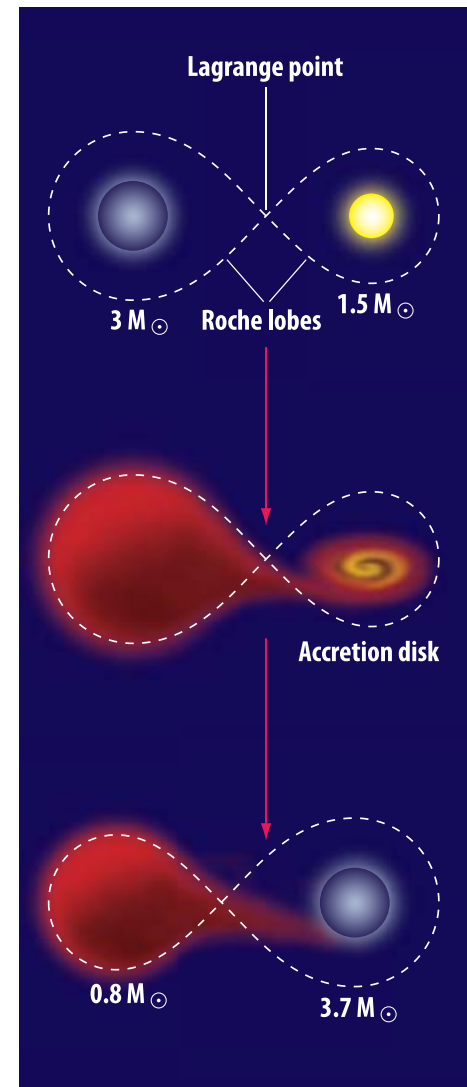
(d) Overcontact binary: Both stars overfill their Roche lobes.

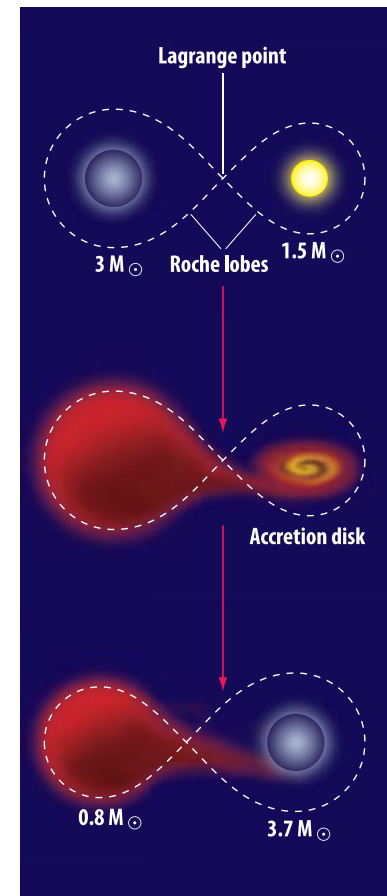
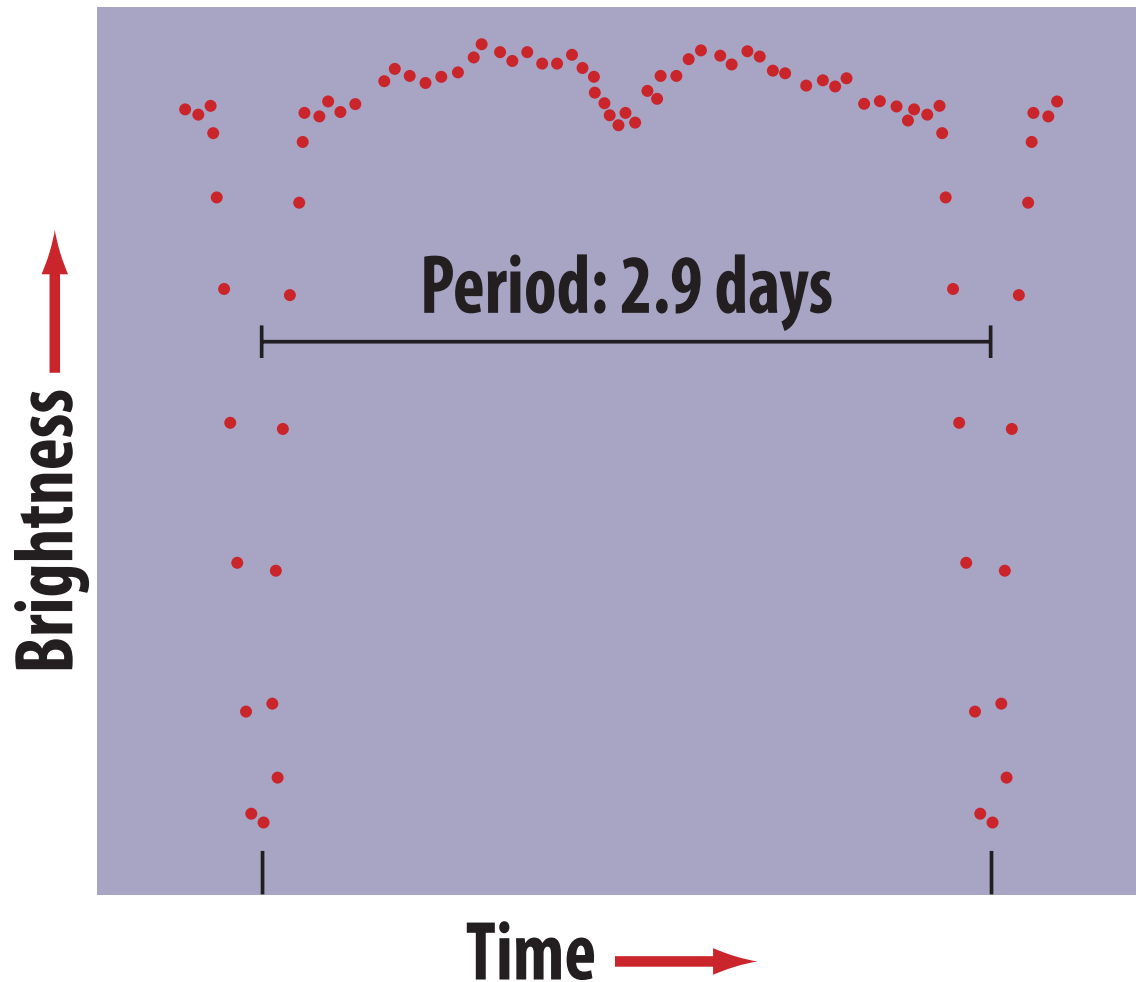
Accretion in Binary Systems

The Algol paradox: Typically in a binary containing a red giant and a main sequence star the red giant should be the more massive one thus explaining its faster evolution. In Algol the opposite is observed!

The diagram shows the evolutionary history of the Algol binary. Initially the more massive star swelled into a red giant and overflowed its Roche Lobe.

So much matter was transferred onto its main sequence companion that the relative masses were reversed (paradox resolved).





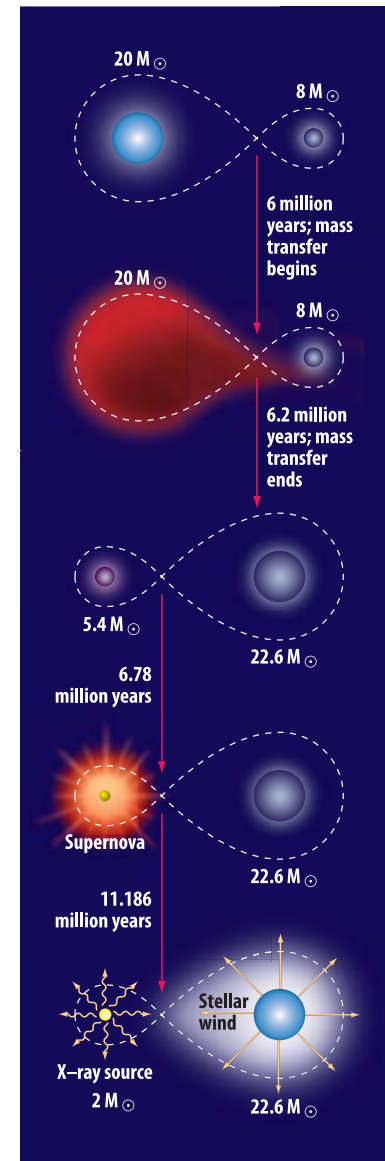
The light curve plotted shows the periodic eclipses that tell us not only the orbital period but also the relative sizes and brightnesses of the two stars.

Start off with a binary containing $20M_{\odot}$ and $8M_{\odot}$ stars. The $20M_{\odot}$ evolves faster to a red giant, overflows its Roche Lobe and transfers enough matter to the other star to reverse the mass ratios.

Although the evolved star has lost most of its mass it still proceeds towards a **core collapse supernova** since the evolution is determined by the core of the star.

Important note: *A binary remains intact when the less massive star explodes.*

We are left with a binary consisting of a black hole or neutron star with a massive main sequence star companion. A second more dramatic phase of mass transfer onto the compact object now begins.



Evolution of a binary

Accretion onto a Massive Object

Matter in a gravitational field has **gravitational potential energy**. This potential energy is converted into **kinetic energy** when matter is accreted onto a massive object.

The energy released in units of mc^2 when dropping a mass m into :

the sun: $E_{\text{released}} \sim 10^{-6} mc^2$

a black hole : $E_{\text{released}} \sim 0.06 - 0.42 mc^2$

How does the efficiency of accretion depend on the spin of a black hole?



Accretion onto a Massive Object

Radiation from the accretion disk will **scatter off the infalling material** and exert an outward force.

There is an upper limit on how bright an accreting object may be such that it doesn't blow away the accreting material.

The upper limit is called the **Eddington luminosity** of the accreting object.

The balance between the radiation force and the gravitational force allows one to derive the Eddington luminosity.

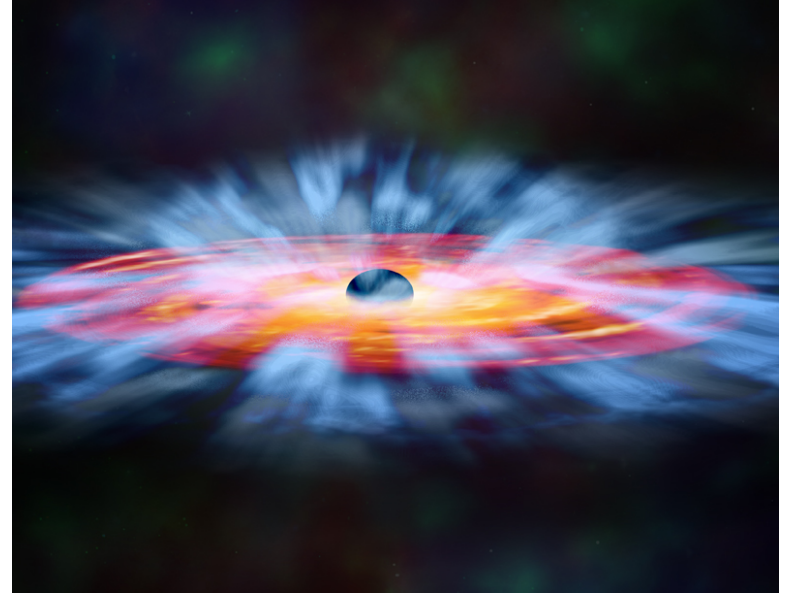


$$L_{Edd} = 1.3 \times 10^{38} \left(\frac{M}{M_{\odot}} \right) \text{ erg/s}$$

Accretion onto a Black Holes

Energy released from accretion of mass onto a black hole goes into:

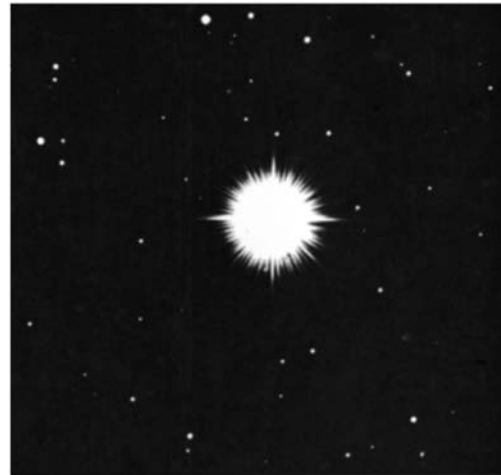
1. Heating the accretion disk
2. Electromagnetic radiation emitted
3. Outflowing winds in some cases
4. Powerful jets in some cases
5. The remaining mass and energy is sucked in by the black hole



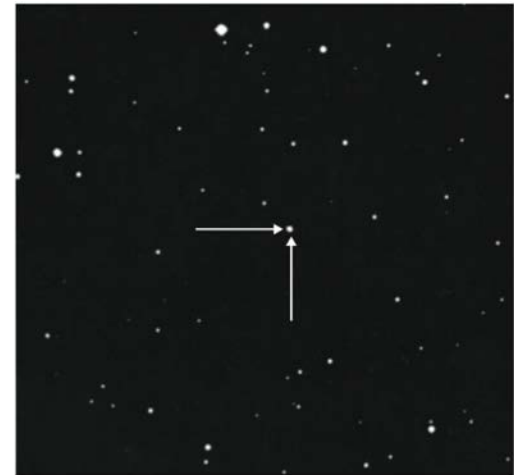
Examples of Accretion onto Compact Objects: Novae

A **nova** is an explosion that occurs in a binary system comprised of a white dwarf and a companion star overflowing its Roche lobe.

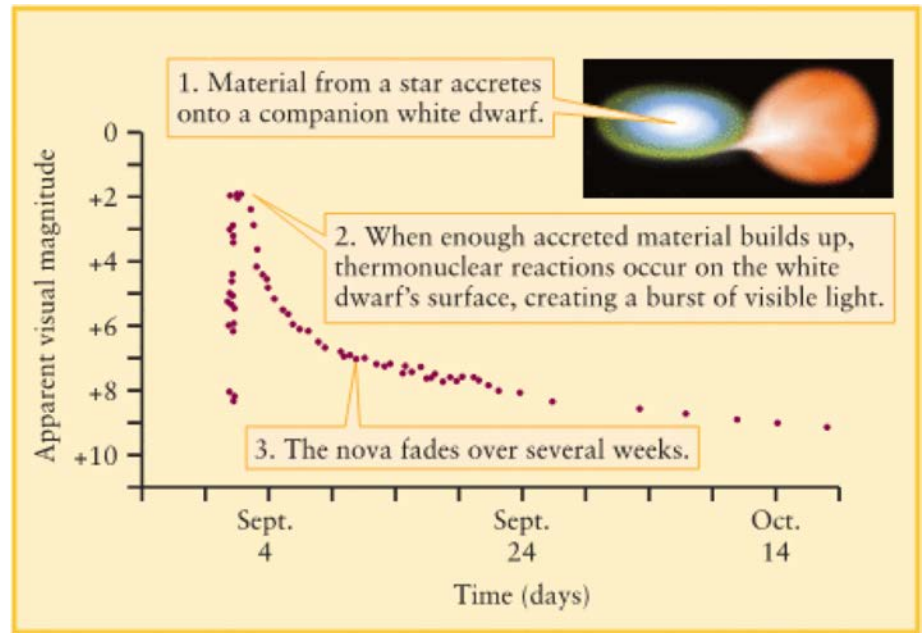
Mass transfer deposits H on the white dwarf. As the H is compressed on the surface its temperature rises and when it reaches $\sim 10^7$ K fusion begins. The onset of fusion releases enough energy to blow off the accreted layer.



(a) Nova Herculis 1934 shortly after peak brightness



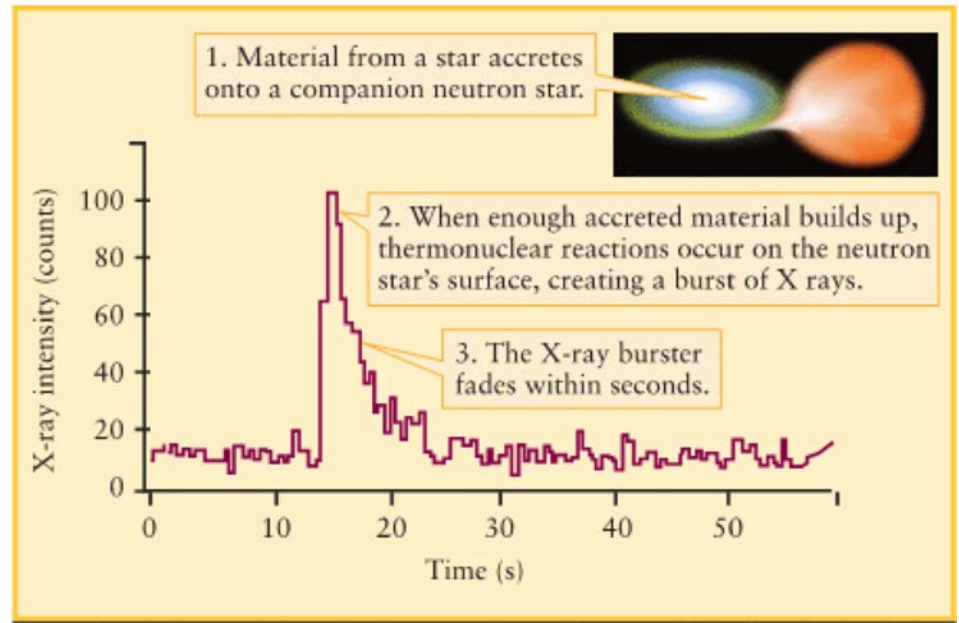
(b) Two months later



Examples of Accretion onto Compact Objects: **Bursters**

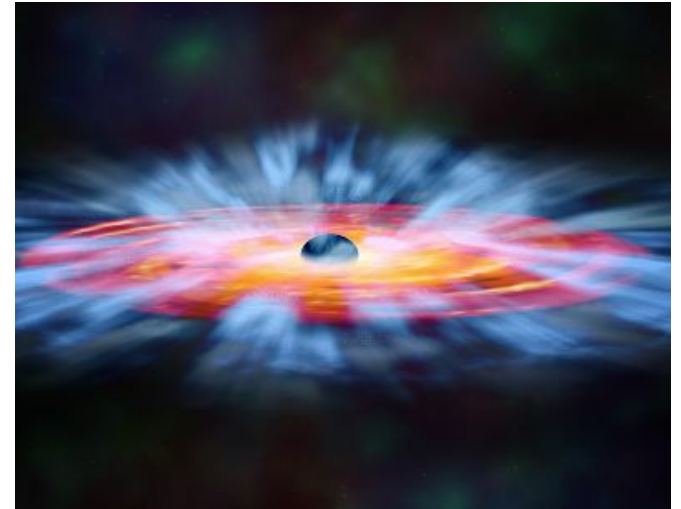
A **burster** is an explosion that occurs in a binary system comprised of a neutron star and a companion star overflowing its Roche lobe. H transferred from the companion star to the surface of the neutron star is compressed and heated. The fusion of H forms a layer of He that gradually increases in thickness.

When the compressed He layer reaches a thickness of about 1m helium fusion ignites explosively raising the surface temperature of the neutron star and emitting a burst of X-rays.



Accretion Disks

Gas captured by a neutron star or a black hole in general does not fall radially inward; because of its angular momentum, the gas forms a swirling disk or vortex. Because the gas is relatively compressible it often gets flattened into an **accretion disk**.



Some properties of accretion disks:

Differential rotation: inner parts rotate faster than outer ones

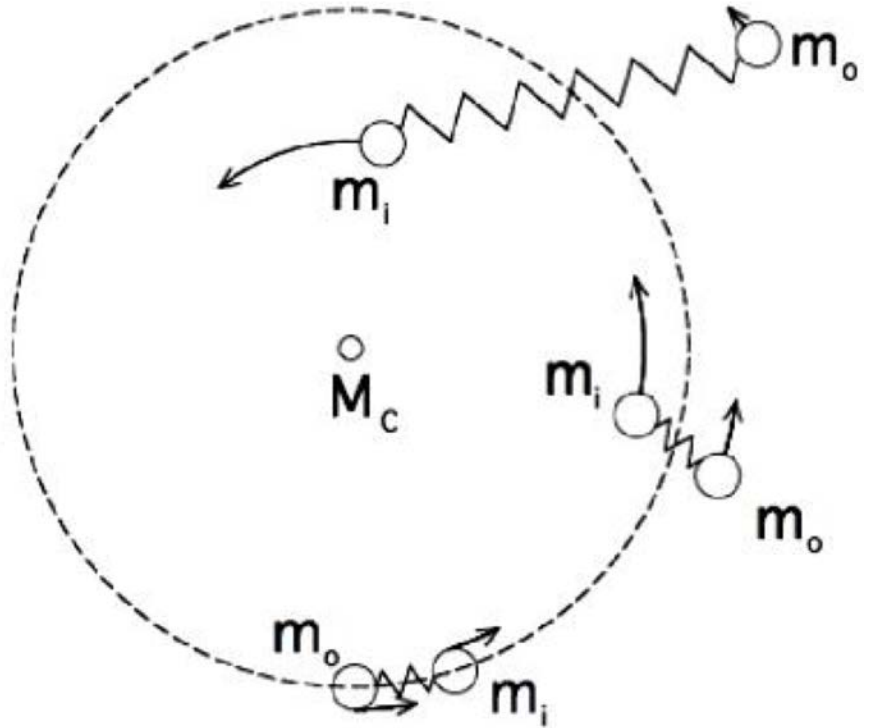
Temperature gradient: inner parts are hotter than outer ones

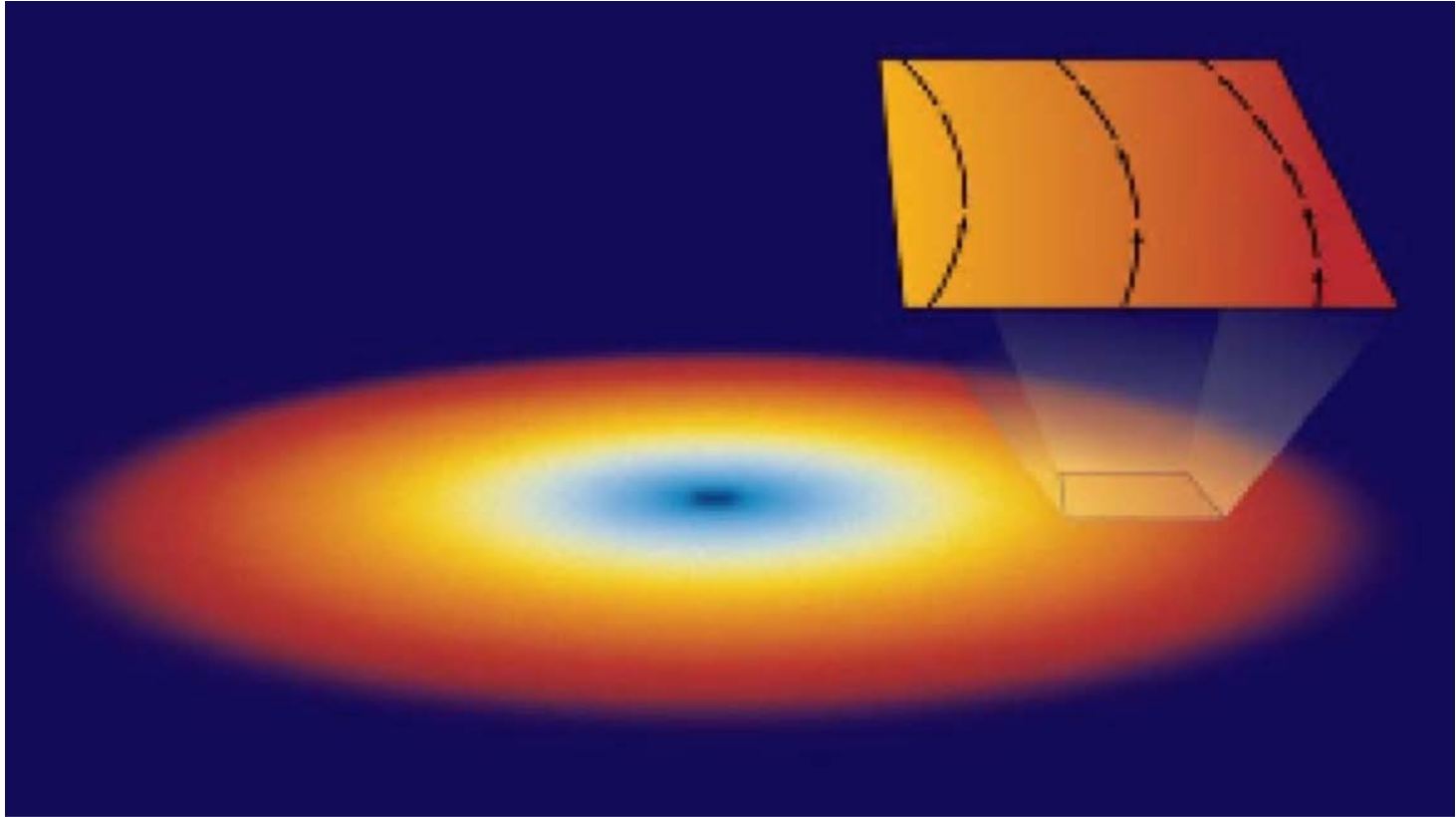
Viscosity: friction produced by magnetic reconnection allows the material to inflow inwards

The Magneto-Rotational Instability (MRI) model for Accretion onto a Black Hole

In a Keplerian disk the inner particle orbits faster than the outer one.

Magnetic fields act as springs between particles. The spring action removes angular momentum from the inner particle making it enter a lower orbit whereas the outer particle gains momentum and enters a larger orbit.





In an **accretion disk** the gas closer to the center is orbiting faster than gas farther out. **Frictional effects transfer angular momentum outwards** allowing the gas to slowly drift inward. Theory indicates that the friction arises from turbulent magnetic fields. The friction heats the gas and the inner parts radiate more than the outer ones.

Simulations of Accretion Disks

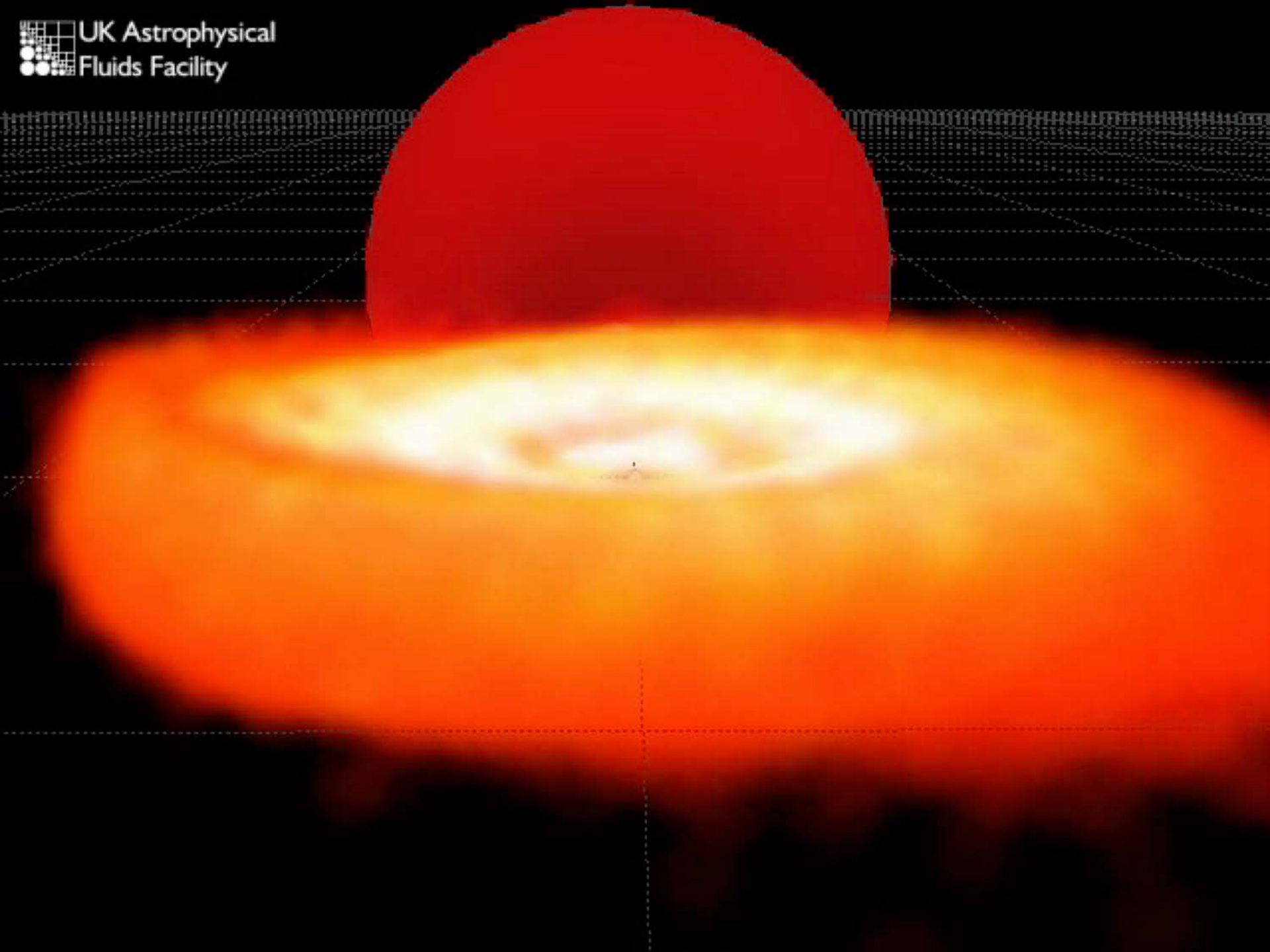
1. **Accretion disc in a binary star system**

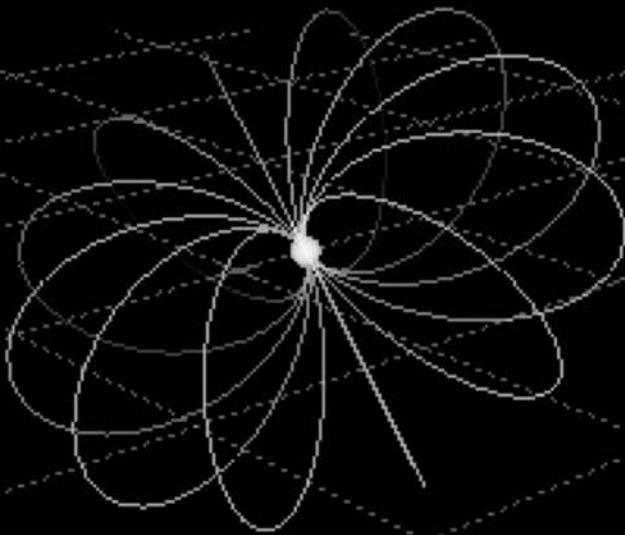
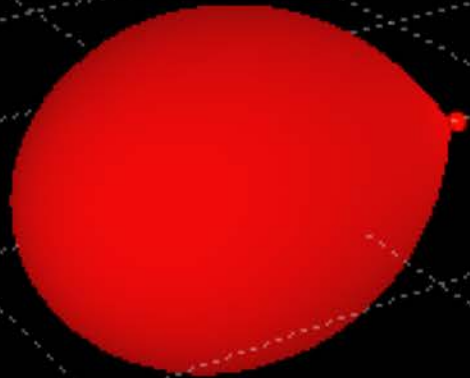
This simulation shows an accretion disc around a white dwarf in a binary star transient system.

2. **The magnetic Cataclysmic Variable *EX Hydrae***

In the binary star system EX Hydrae the two stars are orbiting so close that matter is stripped from the larger (though less massive) star and falls onto its more massive white dwarf companion. The white dwarf in this system has a magnetic field which is so strong that it disrupts the stream of gas drawn from the companion and funnels it toward the nearest magnetic pole. As the white dwarf rotates with respect to its companion the stream "flip-flops" between the two poles.

Thanks to <http://www.ukaff.ac.uk/movies.shtml>



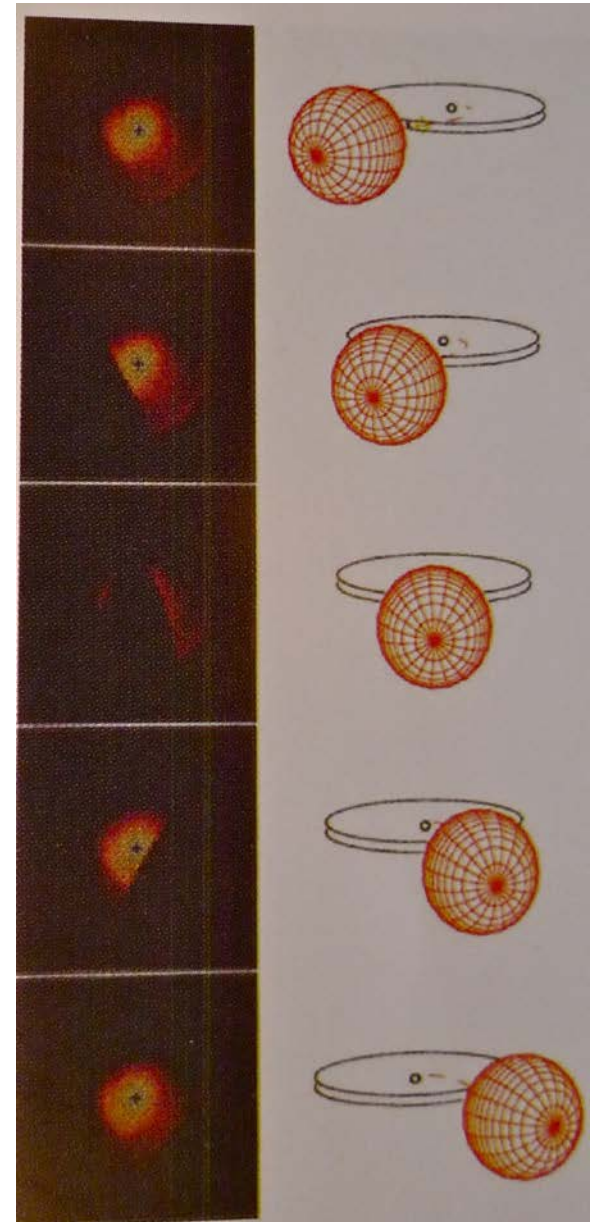


Reconstructing Accretion Disks via Tomography

Some close binaries, like UU Aquarii, are so oriented that the normal star passes in front of the accretion disk once per orbit.

By observing the changes in the brightness and color as the eclipse proceeds, the appearance of the disk can be reconstructed, even though it is too small to be resolved with any telescope.

Keith Horne has pioneered this technique.



Stellar Mass Black Holes: Firming Up the Case

More obvious signatures of stellar mass black holes would be the **dragging of space time** around the black hole, the **BH spin** and ultimately the **BH horizon**.

One significant difference between BHs and other compact objects is that BHs do not have *hard* surfaces.

In a WD or NS when the accreting material reaches the surface it creates a shock that should lead to an observable.

In principle if one could distinguish the radiation from the boundary layer from that of the disk one could distinguish a BH from a NS.