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International Centre for Theoretical Physics

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2292-2

School and Conference on Analytical and Computational Astrophysics

14 - 25 November, 2011

Introduction to Accretion Phenomena in Astrophysics

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Elementary Introduction to Accretion Flows

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Structure of the course

1. **Accretion phenomena in astrophysics**
   - Binary star systems
   - Compact X-ray sources
2. **Spherical Accretion**
   - Hydrodynamic spherical accretion
3. **Accretion discs**
   - Basics of accretion disc theory

- **‘Binary Star** – a real double star, the union of two stars that are formed together in one system by the laws of attraction.’ (William Herschel, 1802).

- Note! 25-50% of all stars in our galaxy are in binaries!

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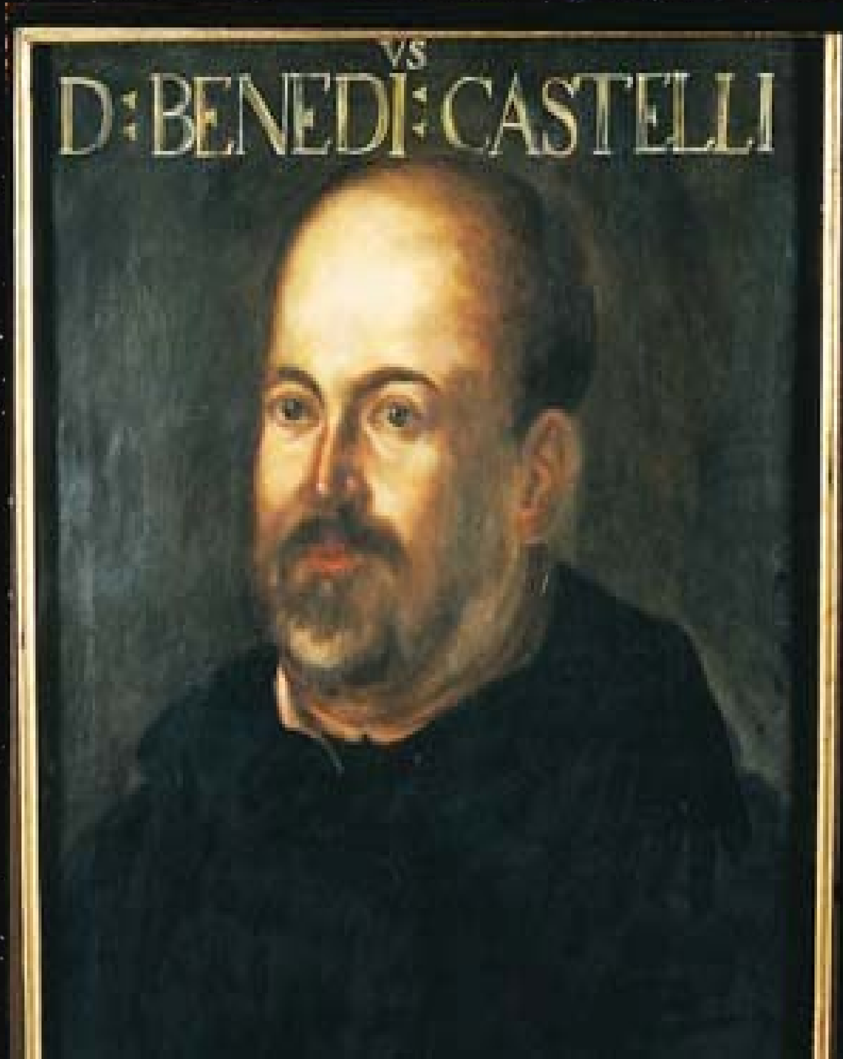
Noel Carl
Canon EOS-20D and 17-40 zoom lens at f/4 piggybacked o
15 x 30 secor

Classification by methods of observation

- Optical binaries (‘optical pairs’, ‘false binaries’).

Example: **Mizar** and **Alcor** in ‘Big Dipper’ (~0.25 light years apart).

Visual (telescopic) binaries



Mizar A and **Mizar B**:

The very first **telescopic binary** discovered by:

1617 - Benedetto Castelli **(Galilei's pupil and Toricelli's teacher).**

(~380AU distance, they take ~1000 years to revolve around each other!)

Spectroscopic binaries

- **Mizar A** was the very first spectroscopic binary: in 1889 **Edward Pickering** found that it is a binary star. This binary is 35 times brighter than the Sun.
- **Orbital period ~20 days.**
- There exist **double-lined (SB2)** and **single-lined (SB1)** spectroscopic binaries.
- Famous SB1 - **Cygnus X-1** System.

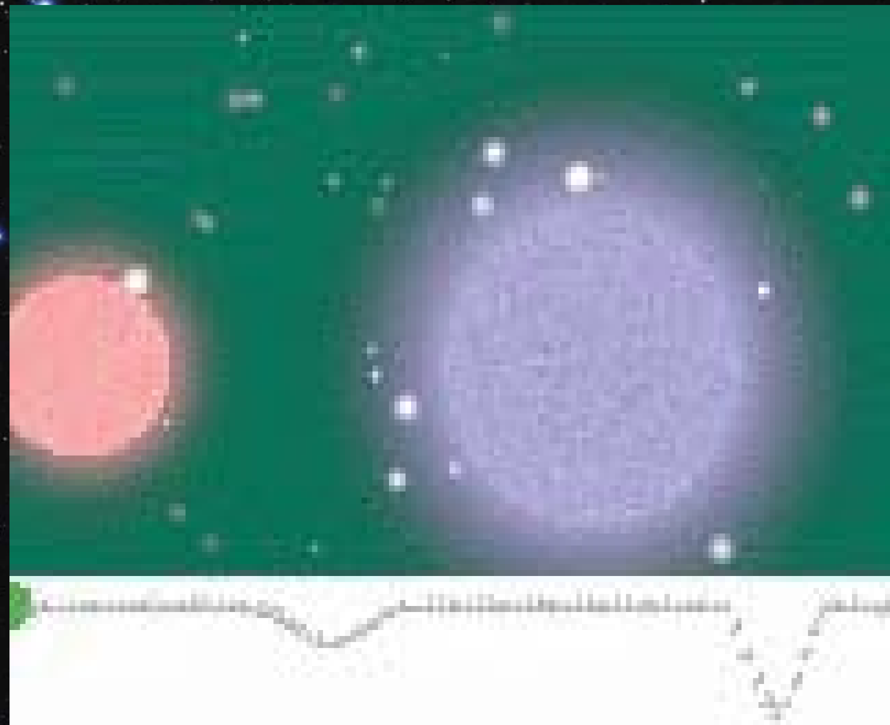
Mysterious Star - Algol

Algol (Beta Persei)

- Geminiano Montanari (astro-nomer and lens- maker (1667):
- Algol's magnitude is usually near-constant at 2.1, but re-gularly dips to 3.4 during the several hour long interval which happens every 2 days, 20 hours and 49 minutes.
- John Goodricke (1764-1786). He was awarded Copley Medal for the solution of the Algol mystery, 1783!

What happens in Algol?

- The orbital plane of the two stars lies so nearly in the line of sight of the observer that the components undergo **mutual eclipses!**
- Thus Algols is an Eclipsing Binary!



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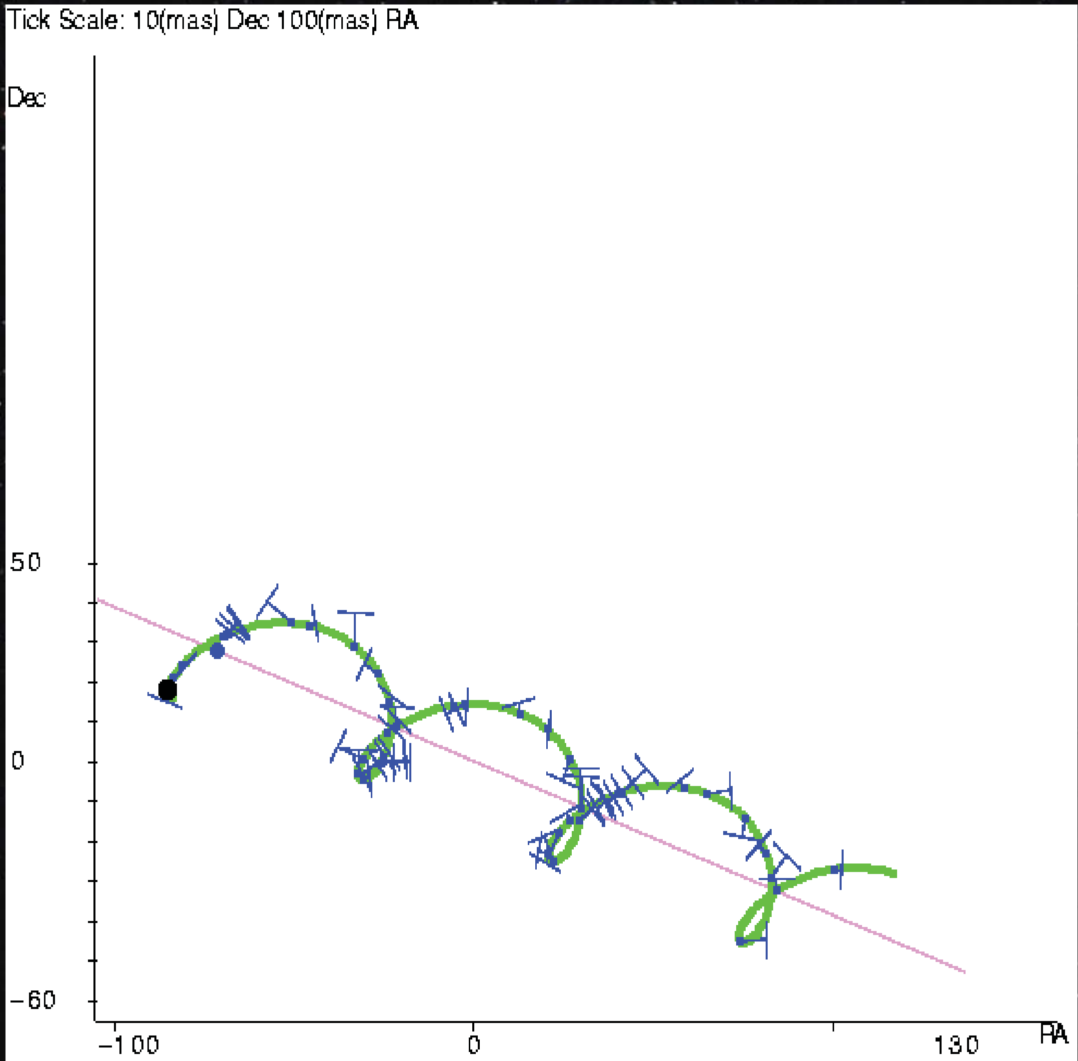
Astrometric Binaries



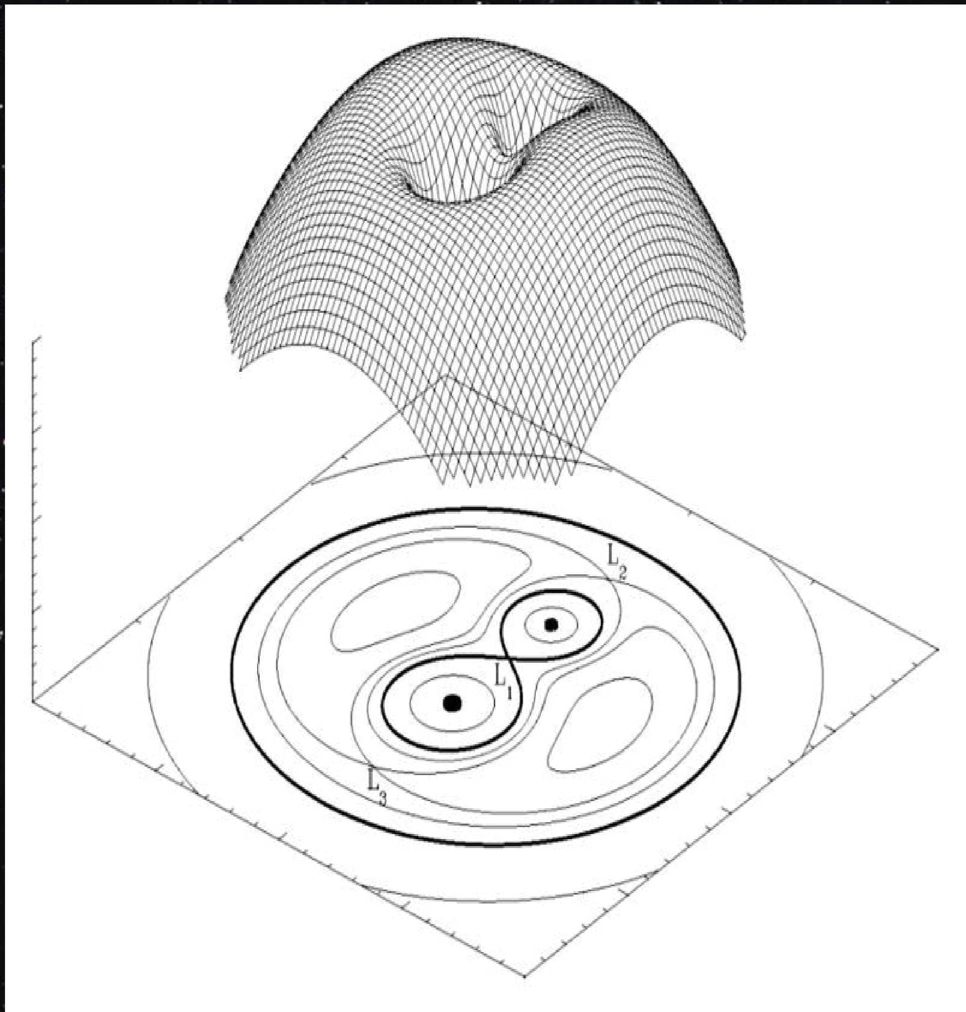
- Relatively nearby stars that seem to orbit around an empty space – ‘wobbles’ superimposed on their proper motion (sinusoidal path on the sky):

Sirius B was discovered first as an astrometric binary in this way, and only later telescopes became good enough to detect the faint companion in the glare of the primary star.

Typically D<10pc.

- This way it is possible to find extrasolar planets as well.

Roche Lobe



- The **Roche lobe** is an approximately tear-drop shaped spatial region around a star in a binary system within which orbiting material is gravitationally bound to that star. It is bounded by a critical gravitational equi-potential, with the apex of the tear-drop (the apex is at the Lagrange L point of the system) pointing towards the other star.
- If the star expands past its Roche lobe, then the material outside of the lobe will fall into the other star.
- This can lead to the total disintegration of the object, since a reduction of the object's mass causes its Roche lobe to shrink.

Classification by configuration

- ***Detached binaries*** are a kind of binary stars where each component is within its **Roche Lobe**. No major impact on each other, stars essentially evolve separately.
- ***Semidetached binary stars:*** one of the components fills its Roche lobe and the other does not. Gas from the surface of the Roche lobe filling component (donor) is transferred to the other, accreting star. The mass transfer dominates the evolution of the system; the inflowing gas may form accretion disc around the accreting star. Examples: X-ray binaries and Cataclysmic variable stars.
- ***A contact binary:*** both components fill their Roche lobes. The uppermost part of the stellar atmospheres forms a *common envelope* that surrounds both stars; the friction of the envelope brakes the orbital motion, the stars may eventually merge.

The Big Dipper

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15 x 30 second ISO 1600 exposures

Algol paradox!

- Although components of the binary are formed at the same time and massive stars are supposed to evolve much faster than the less massive ones, it was observed that the more massive Algol A (5 times heavier!) is still in the main sequence, while the less massive Algol B is a subgiant at a later evolutionary stage.
- This paradox is solved by mass transfer – **accretion**!

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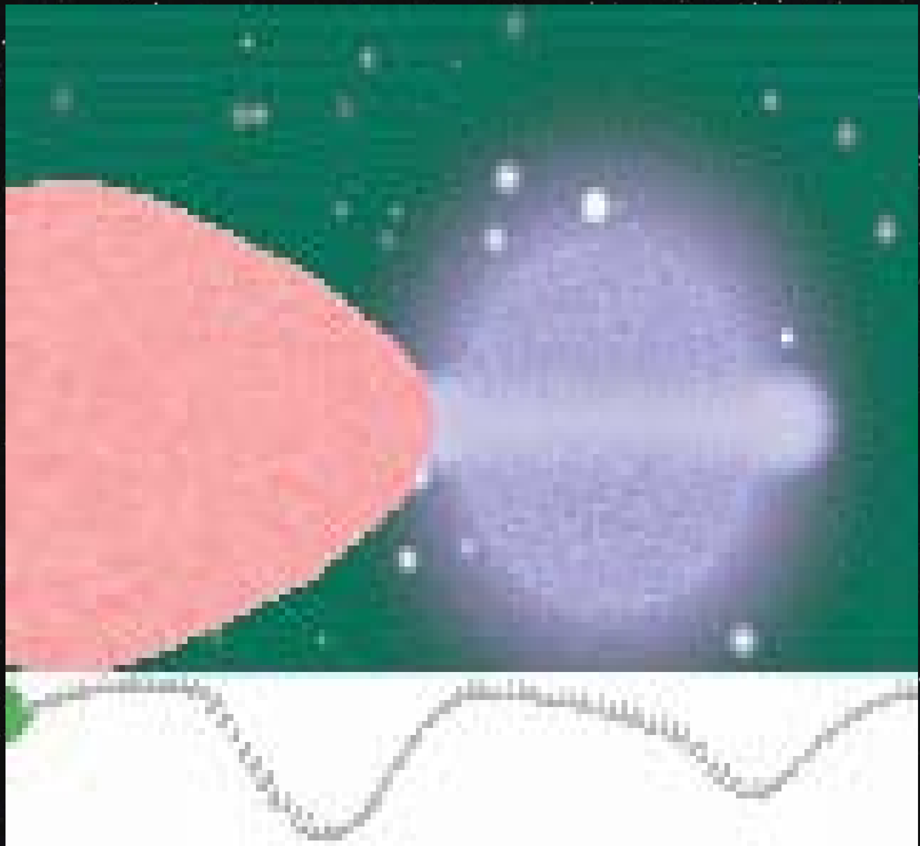
Mass transfer & accretion in binaries



- As star increases in size during its evolution, it may exceed its Roche lobe and some of its matter may fall into a region where the gravitational pull of its companion star is larger.
- The process is known as Roche Lobe overflow (RLOF), the overflowing matter or falls radially (spherical accretion) or forms an accretion disc.
- The mass transfer happens through the first Lagrangian point. It is not uncommon that the accretion disc is the brightest (and thus sometimes the only visible) element of a binary star.

Compact X-ray sources

- June 18, 1962: Launch of **'Aerobee'** rocket carrying three Geiger counters (Giacconi et al. 1968);
- End of 60's – about 20 sources, most in our galaxy, one of them (Cygnus X-1) variable. The brightest one: Sco X-1 (1-10 keV);
- 1966: optical counterpart was located at the position of Sco X-1: 12th-13th magnitude star;
- 1967 **Shklovskii model**:, he proposed that X-rays come from high-temperature gas flowing onto a massive neutron star from a close binary companion.

Early history of the accretion theory

- **(1948) Von Weizsaker:** *'The rotation of cosmic gas masses'*, Z. Naturforsch, **3a,** 524 (1948)
- **(1952) Lust:** Z. Naturforsch, **7a,** 87 (1952)

[In connection with the evolution of early solar nebula, derived some imortant equations of the disc accretion.]

- **(1952) Bondi:** *'On Spherically Symmetric Accretion'* MNRAS, **112,** 195 (1952).

[Analytic theory of hydrrodynamic, spherically symmetric accretion.]

- **(1964) Hayakawa & Matsuoka** *'Origin of Cosmic X Rays'* Prog. Theor. Phys. Suppl.**30,** 204 (1964)

[Argued that gas accretion in close binaries might be a source of X-ray emission.]

- **(1968) Prendergast & Burbridge:** *'On the nature of some galactic X-ray sources'* Ap.J. Lett., **151,** L83 (1968).

[Argued that gas flowing onto a compact star from a binary companion would have too much of angular momentum to accrete radially. Instead the gas would form approximately Keplerian, thin accretion disc.]

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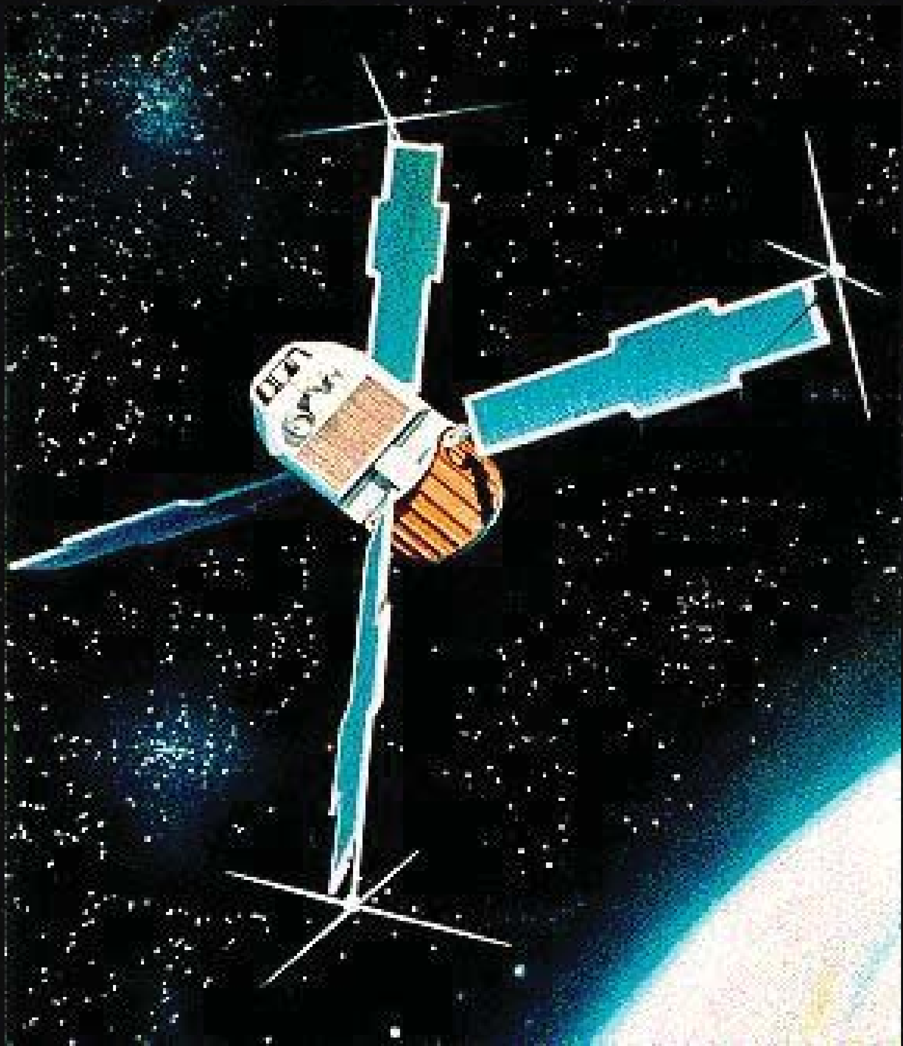
UHURU Revolution



- December 12, 1970 **'UHURU'** was launched from Kenya (2-20 keV band) – it discovered about 300 new discrete X-ray sources.

Most significant breakthrough:

- Detection of **X-rays from binary stellar systems** (about 100 (!) optical companions).
- Discovery of **binary X-ray pulsars**.

General Statistics of X-ray sources

- Distance range: hundreds of parsecs to tens of kilo-parsecs;
- Luminosity and variability ranges:

$$\mathbf{L \sim 10^{33} - 10^{38}\ erg/s}$$

$$\mathbf{10^{-3}s < t < 10^{7}s}$$

Two kinds of stellar systems:

- **Population I systems**: Optical components are O or B supergiants: very massive, very luminous and very young stars. They are relatively rare because they also don't live long. Representative example: Cygnus X-1.
- **Population II systems**: Sun-like stars, later spectral class, longer lifetimes, more common. Example: Her X-1.

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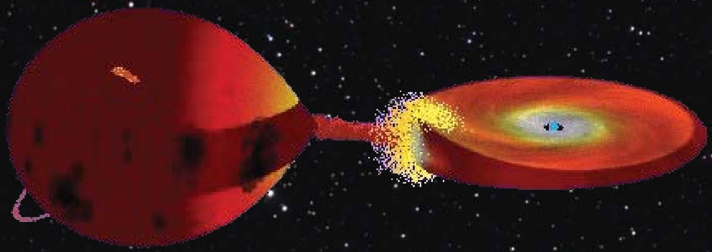
Cataclysmic Variables



- Binary containing a white dwarf and a companion star (usually a red dwarf).
- Blue stars with rapid and strong variability.
- Strong **UV** and **X-ray** emission.
- Peculiar emission lines
- Size: roughly Earth-Moon system.
- Orbital periods: **1-10 h.**
- Energy sources: accretion and nuclear fusion.

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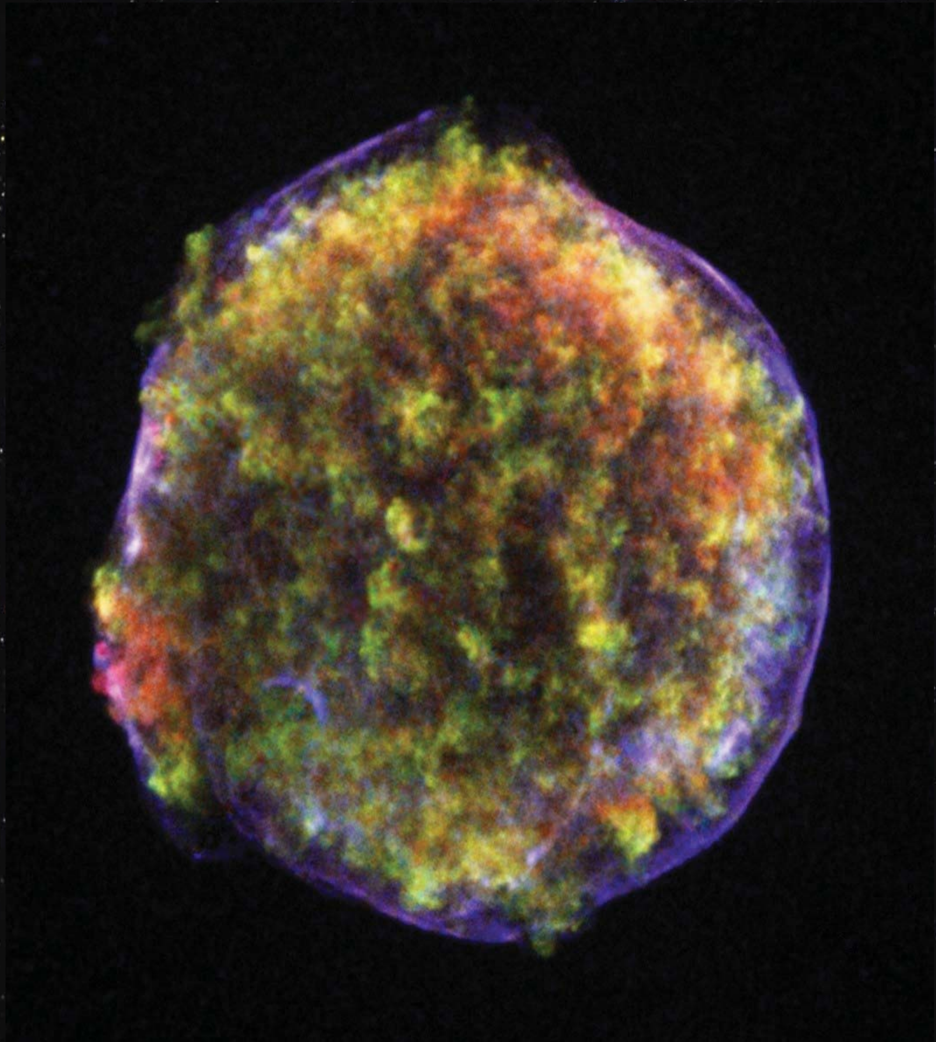
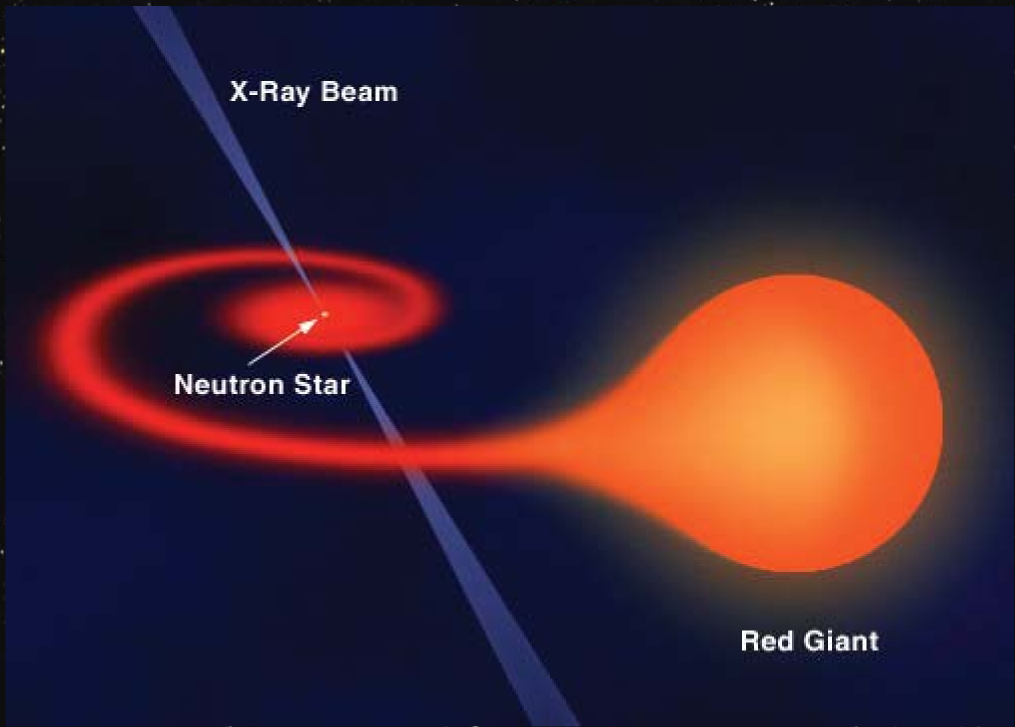
Novae and runaway stars



- If a white dwarf has a companion star that overflows its Roche lobe, it steadily accrete gases by its intense gravity, compressed and heated to very high temperatures.
- Hydrogen fusion can occur on the surface, the enormous amount of energy is liberated. The remaining gases blown away from the white dwarf's surface. The result - bright outburst of light, known as a **nova**.
- In extreme cases this event can cause the white dwarf to exceed the Chandrasekhar limit and trigger a **supernova**, destroying the entire star, and causing a **runaway star**. Example: of such an event is the supernova **SN 1572**, observed by *Tycho Brahe*.

X-ray pulsars



- Short periods:
- **Her X-1**: 1.24s,
- **SMC X-1**: 0.71s

For Her X-1 spectral cyclo-tron line was measured that alowed to estimate magnetic field strength as:

$B \sim 10^{12}$ G

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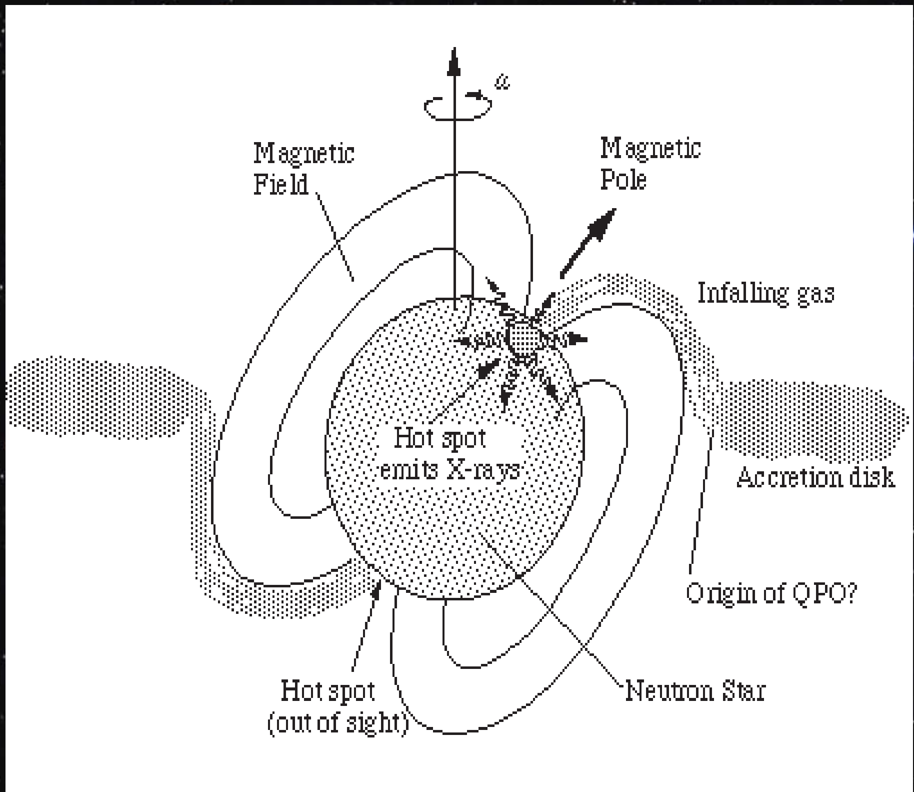
Prototype X-ray pulsar – Her X-1



- Pulsation period: 1.24s.
- Orbital period: 1.7 days.
- ‘On-Off’ cycle: 35 days.
- Mass:

$$0.4 < M_x/M_\odot < 2.2$$

$$1.4 < M_{opt}/M_\odot < 2.8$$

Black hole candidates: Cygnus X-1

- The x-ray source with the widest range of time variability;
- 5.6 day period single-lined spectropscopic binary
- The milisecond variability sets the size of the X-ray source:

$$R < c\,\Delta t \sim 300 \text{ km}$$

- Optical star: HDE 226868 - 9th magnitude supergiant with 20-40 solar masses.
- Compact object's mass: most likely about 10 solar masses, but the rigorous lower limit:

$$M_x > 3.4\, M_\odot$$

- Distance: ~2.5kpc

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Bursters

- Usually located in the galactic bulge, so they are a subclass of Galactic Bulge Sources (GBS);
- Soft X-ray spectrum;
- Low luminocities:

$$L_x < 10^{36} \text{ erg/s}$$

- No eclipses and No periodic pulsatons (with recently dis-covered **notable exception**:

  Pulsating Burster GRO J1744-28
- **Type I bursts**: come in intervals from hours to days;
- **Type II bursts**: on timescales from seconds to minutes **('Rapid Burster').**

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