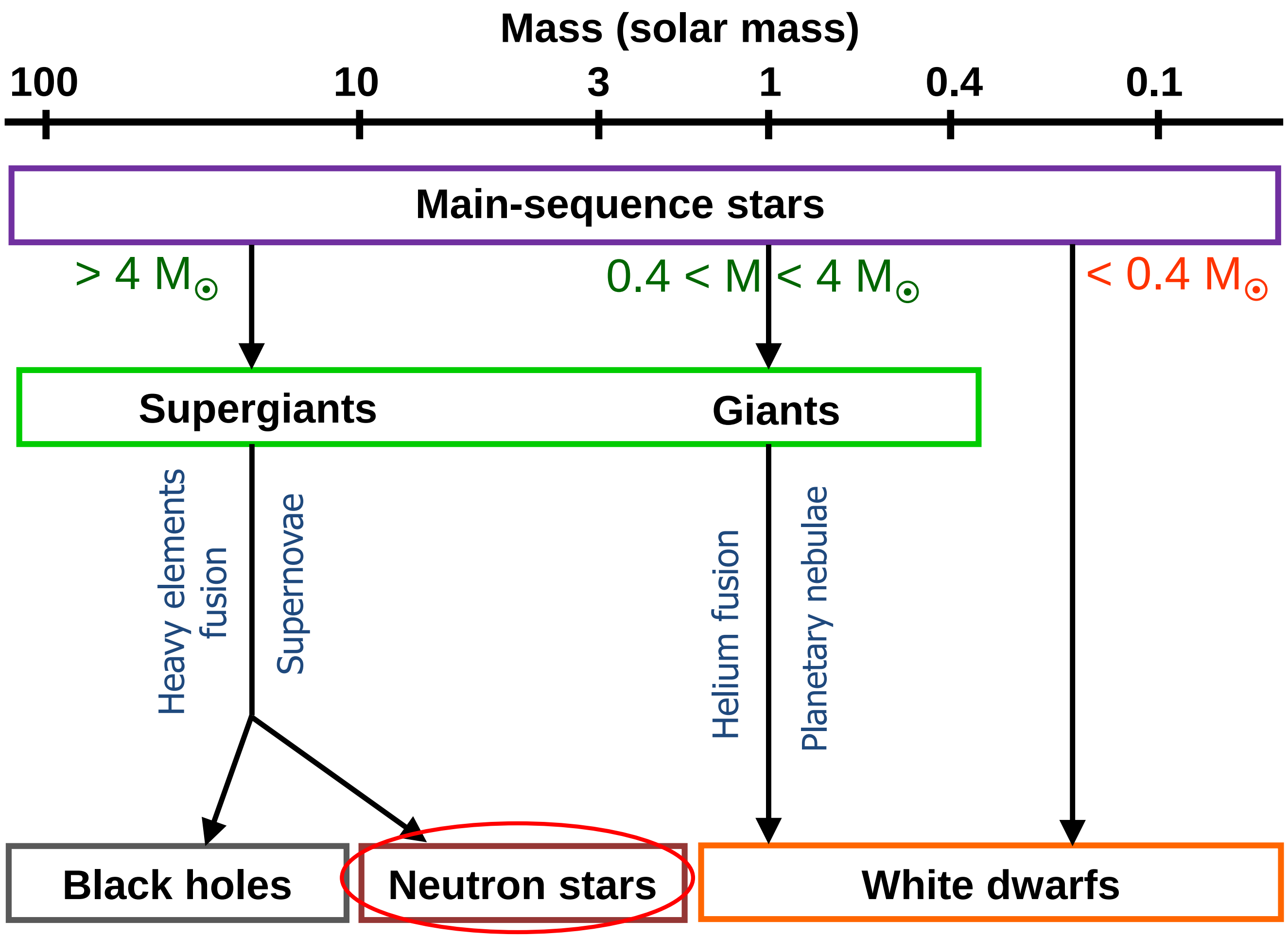
Chapter 12

Neutron stars (中子星)

Previously, we talked about the fate of stars…

star's mass



"final" mass

BH: core's mass > 3 $M_\odot$ becomes black hole

NS: core's mass < 3 $M_\odot$ supported by neutron degeneracy pressure

WS: core's mass < 1.4 $M_\odot$ (Chandrasekhar limit) supported by electron degeneracy pressure

Neutron stars

12.1 Neutron degeneracy pressure

12.2 Properties of neutron stars

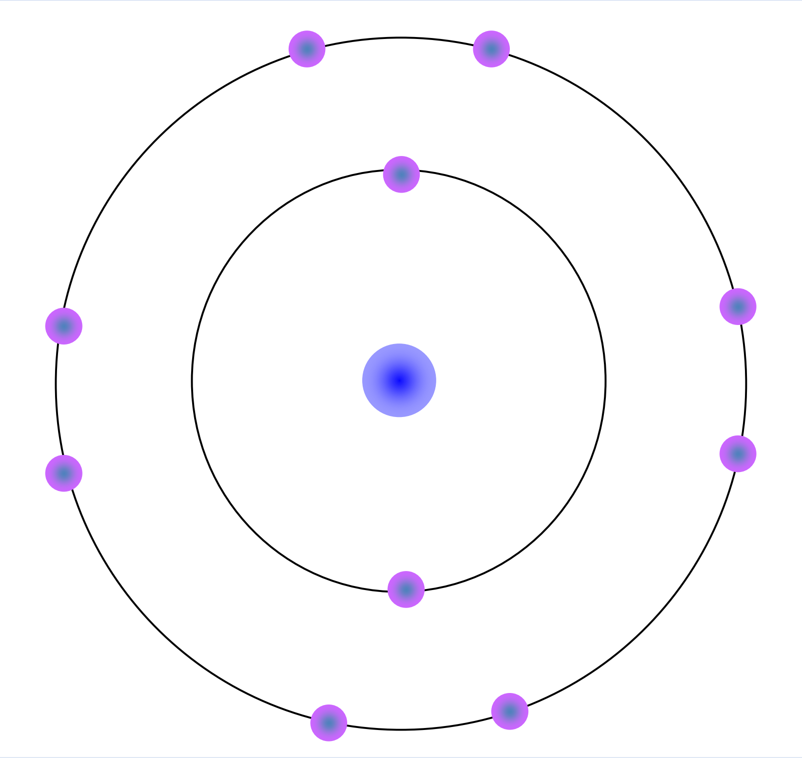
12.3 Pulsars

12.4 Pulsars in binary systems

12.5 Planets around a neutron star

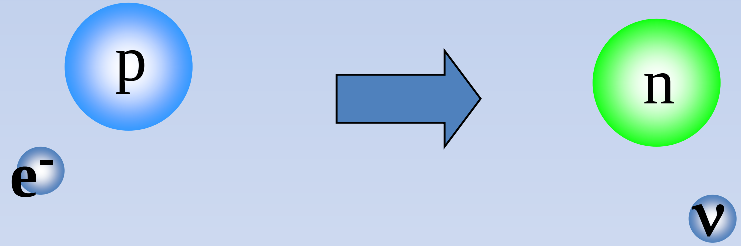
12.1 Neutron degeneracy pressure

- ✓ The core's mass of a dying star > Chandrasehkar limit (1.4 $M_{\odot}$)
- ✓ Gravity is too strong, such that even electron degeneracy pressure cannot support the star.



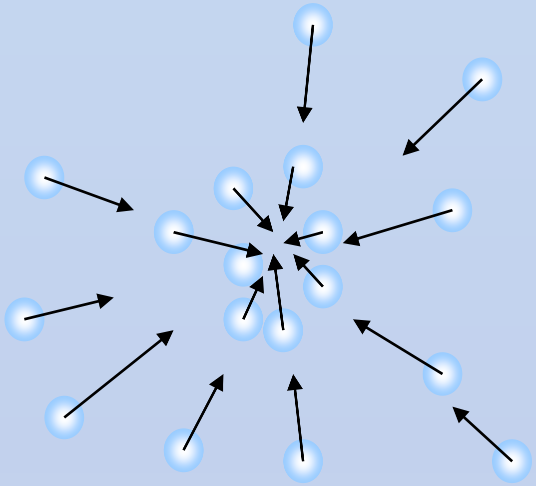
12.1 Neutron degeneracy pressure

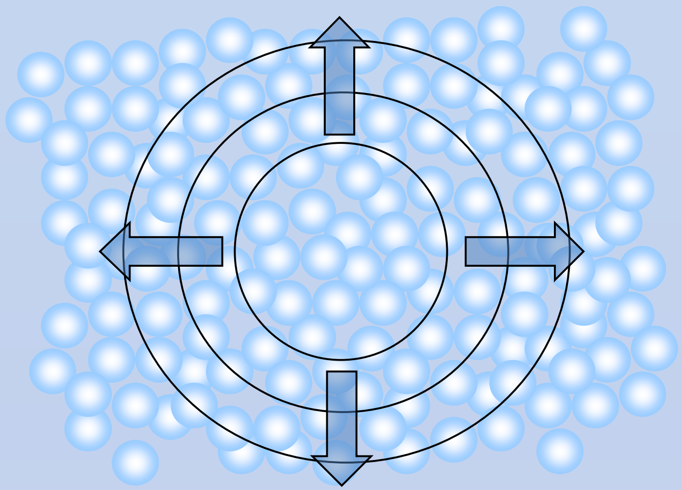
- ✓ Stellar core continues to contract.
- ✓ Electrons are squeezed into atomic nuclei
- ✓ Inverse Beta Decay: electrons combine with protons and become neutron



- ✓ Core becomes neutron-rich matter.
- ✓ Neutron degeneracy pressure (中子简并压力) resists star compression

12.1 Neutron degeneracy pressure





- ✓ Infalling matters press on a *hard* core; a sudden rebounds occur, shock waves are generated and propagate outward.

  (Neutrinos are believed to play an essential role too.)
- ✓ Supernova: explosion of the outer-shells of the star.

12.1 Neutron degeneracy pressure

Gravity is large, but
not too large!

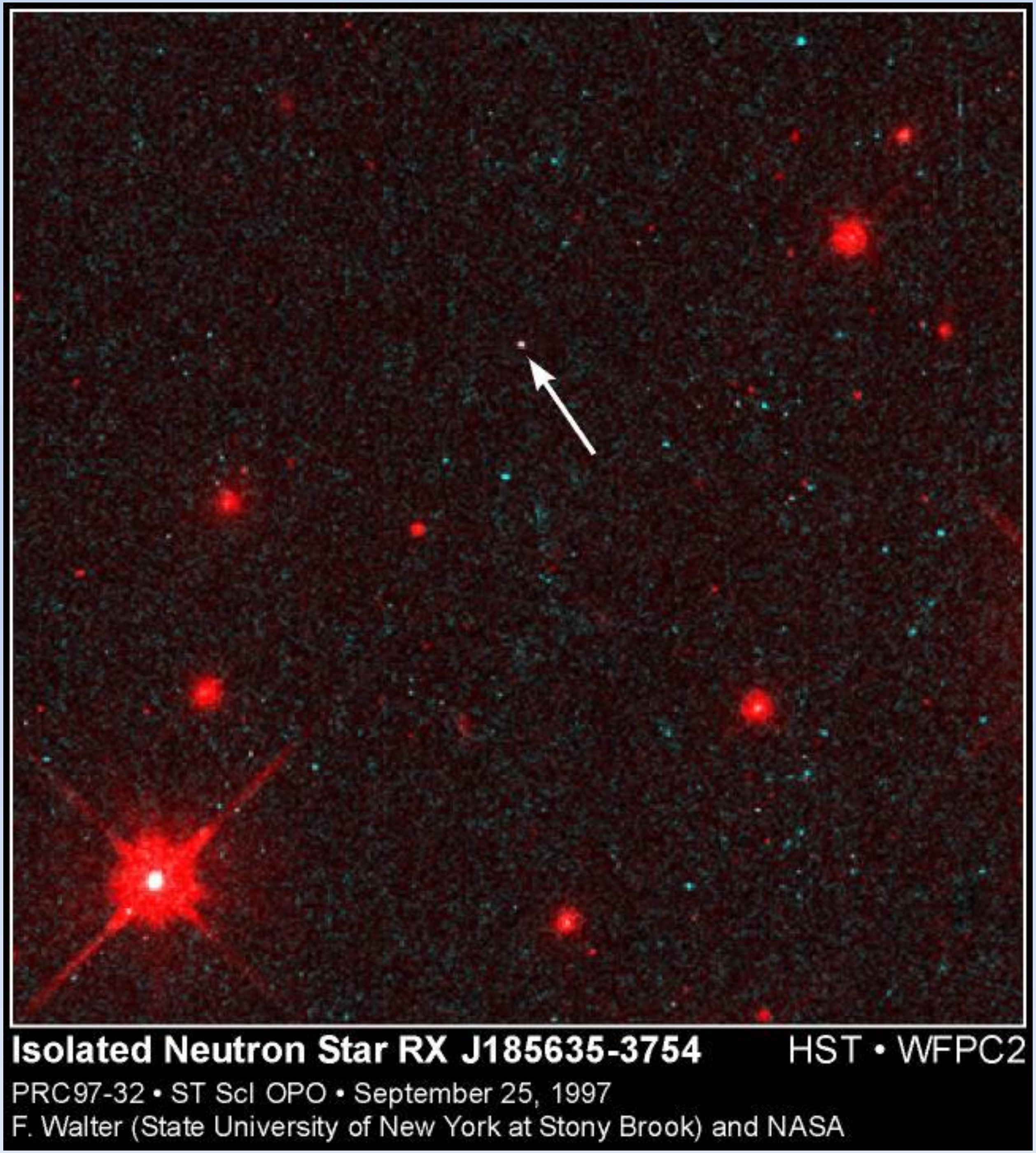
- ✓ If mass of the remaining core $< 3\, M_\odot$, neutron degeneracy pressure will stop further contraction of the core.
- ✓ A stable, very small, but extremely high density neutron star.
- ✓ How about core mass $> 3\, M_\odot$?

  → black hole

12.2 Properties of neutron stars

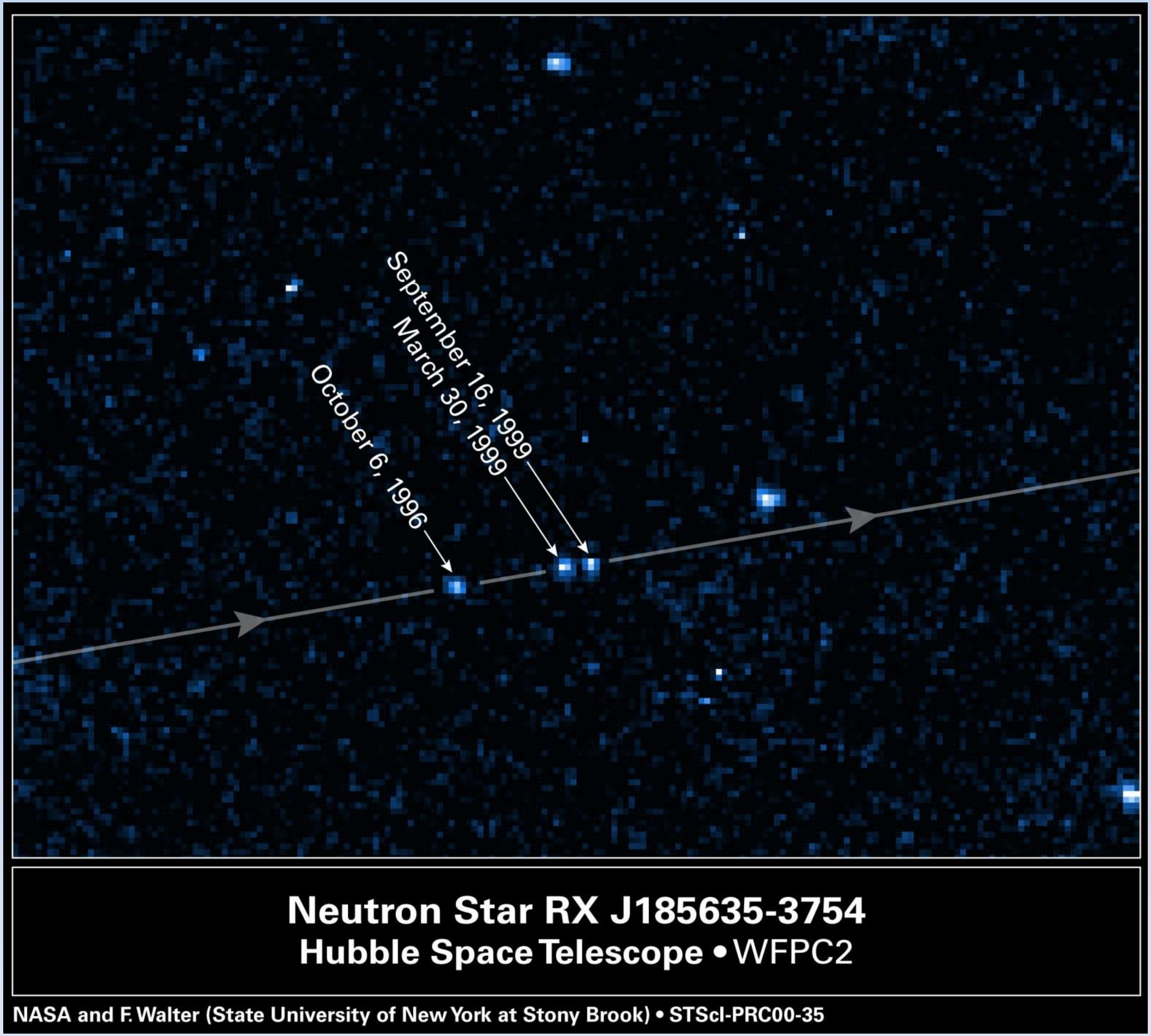
- ✓ Radius ~10-100 km, mass ~1.5 solar masses
- ✓ extremely high density ~ 10^{14} - 10^{15} g cm^{-3} (compress the entire Sun into a city, or the entire Hong Kong into a tablespoon)

e.g., radius ~ 10km, mass ~ $1.4\,M_\odot$ then escape velocity ~ 0.64c ! Relativistic effects important!



First discovered as a X-ray source. Later observe in optical wavelength.

A really dim object (m_V = 25.6)



It's a "runaway" neutron star with speed ~ 100 km/s.

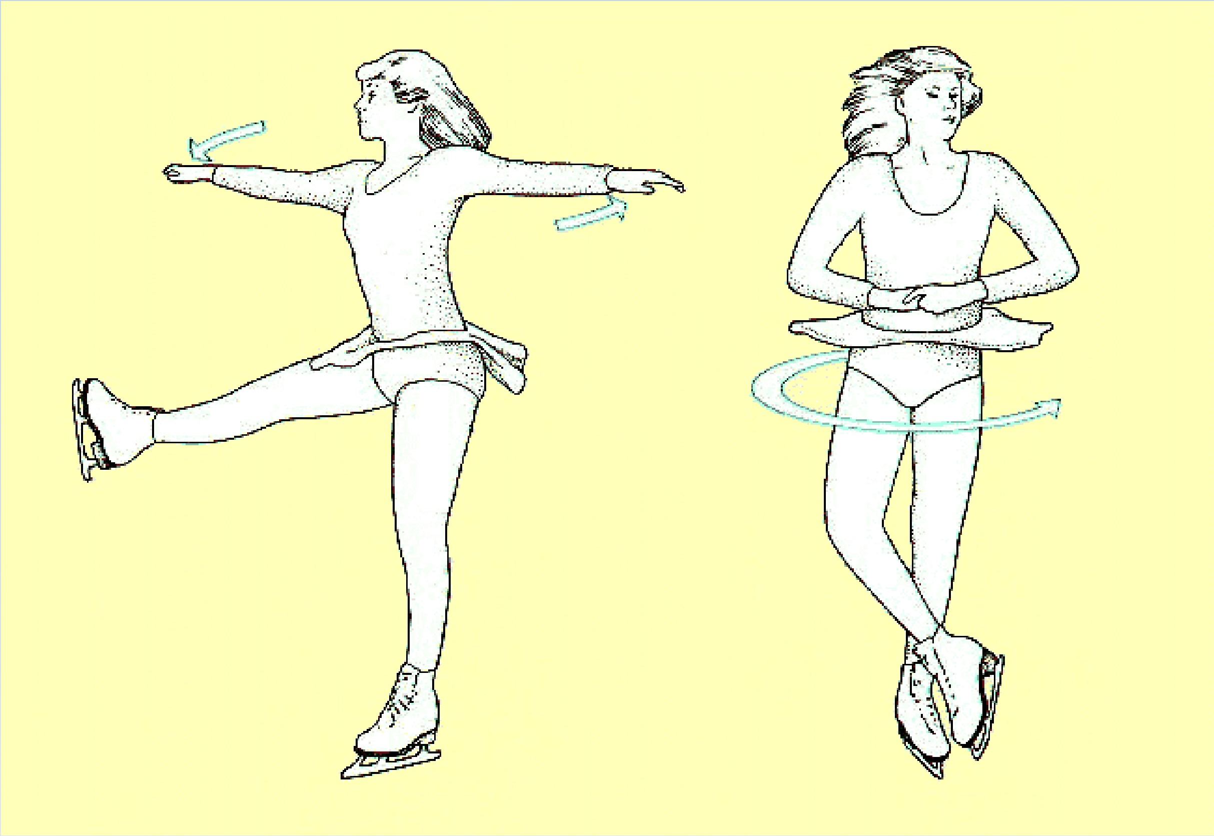
12.2 Properties of neutron stars

- ✓ Extremely strong gravity on the surface.

  → a man would weight 1 million tons there.
- ✓ All surface features have collapsed; there is no "mountain"

12.2 Properties of neutron stars

- ✓ Conservation of angular momentum, a contracting core will spin faster and faster



12.2 Properties of neutron stars

- ✓ A neutron star spins rapidly (~ up to few thousands times per second)
- ✓ Angular speed increases with $1/R^2$:

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

- ✓ periods of luminosity are highly stable and precisely measured (up to 17 digits !)

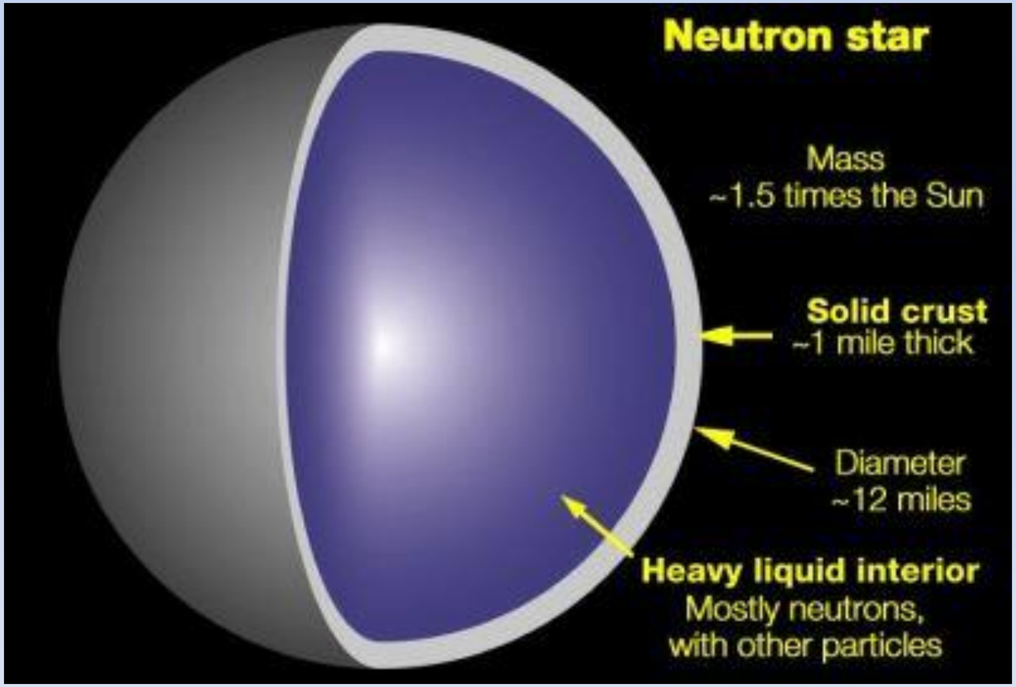
12.2 Properties of neutron stars

- ✓ Magnetic field lines are "frozen in" during the contraction.
- ✓ The magnetic flux of the rotating star ($\Phi \sim BA$) is unchanged.
- ✓ As contracting, $B_i R_i^2 = B_f R_f^2$ then $\boxed{B_f = B_i R_i^2 / R_f^2}$
- ✓ A typical neutron star has a really strong field $\sim 10^{12}$ gauss (for comparison, B field strength ~0.5 gauss on the surface of Earth).

12.2 Properties of neutron stars

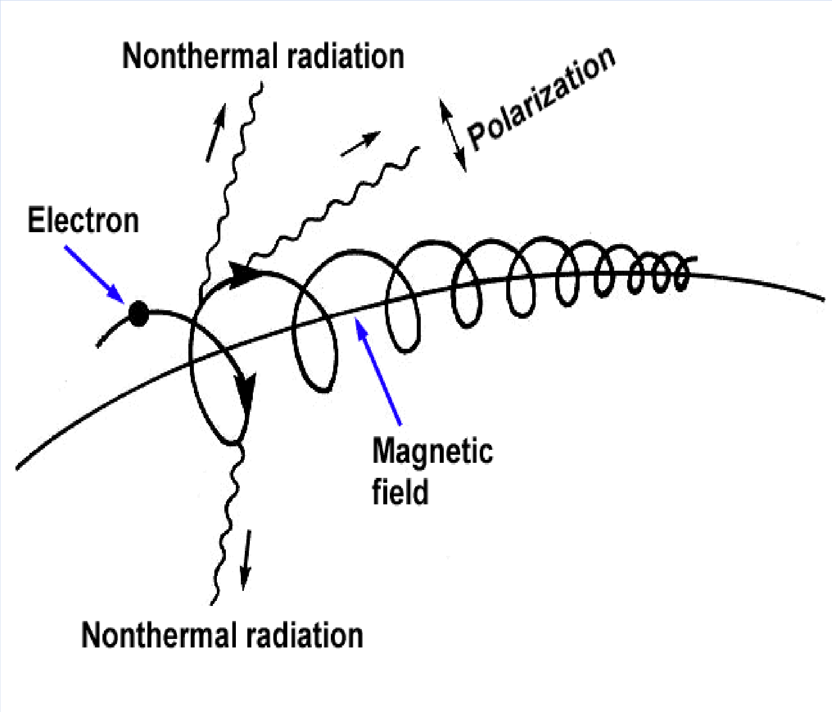
Theoretical model

- ✓ A solid, crystal crust of heavy nuclei.
- ✓ Superconducting fluid of mainly neutrons in the interior.
- ✓ Solid core may exist.

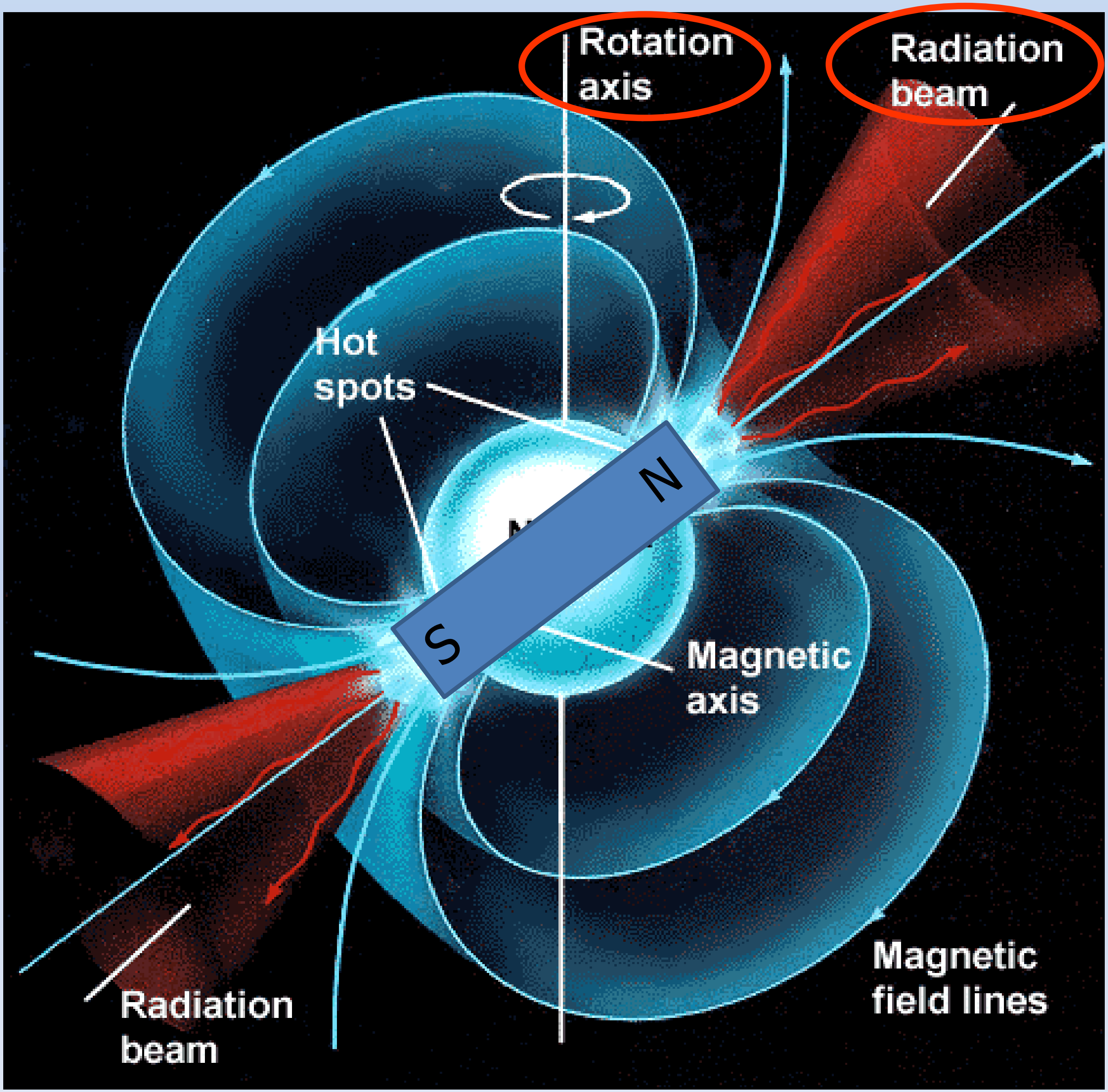


12.3 Pulsars

Neutron stars emit EM radiation (besides thermal emission). How?



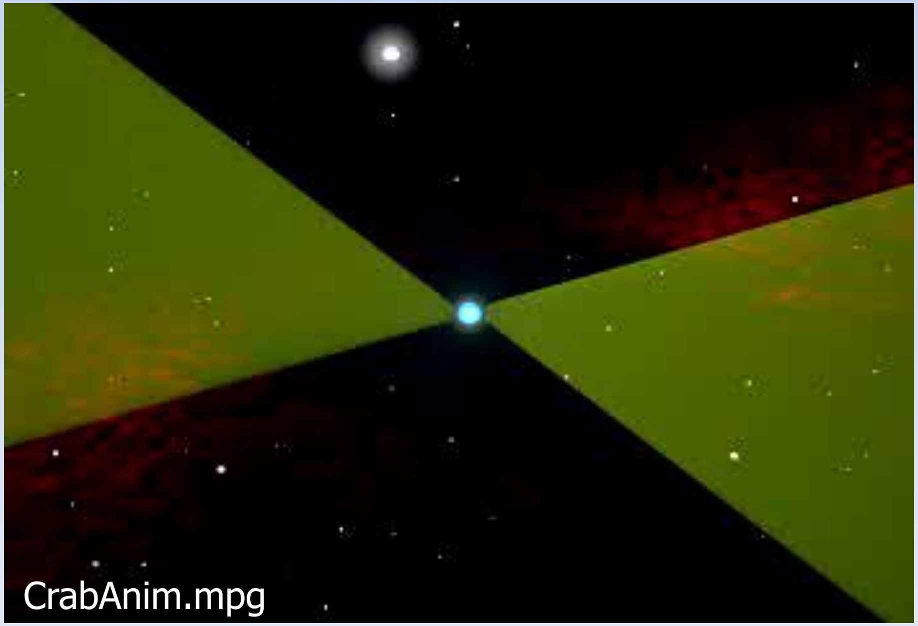
- ✓ A very strong field ~10^{12} gauss in neutron stars
- ✓ Charged particles accelerated and emits radiation from X-rays to radio waves.

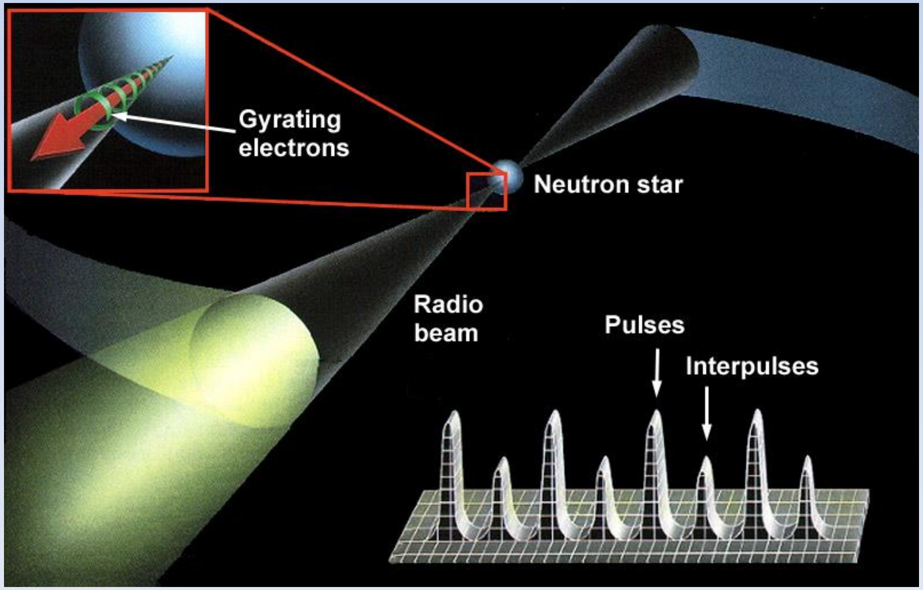


Rotation axis
Radiation beam
Hot spots
N
S
Magnetic axis
Radiation beam
Magnetic field lines

12.3 Pulsars

- ✓ Lighthouse effect (灯塔效应): beams of radiation emitting from the magnetic poles rotating with the neutron star.
- ✓ Highly regular and rapid pulses as seen on Earth.





12.3 Pulsars

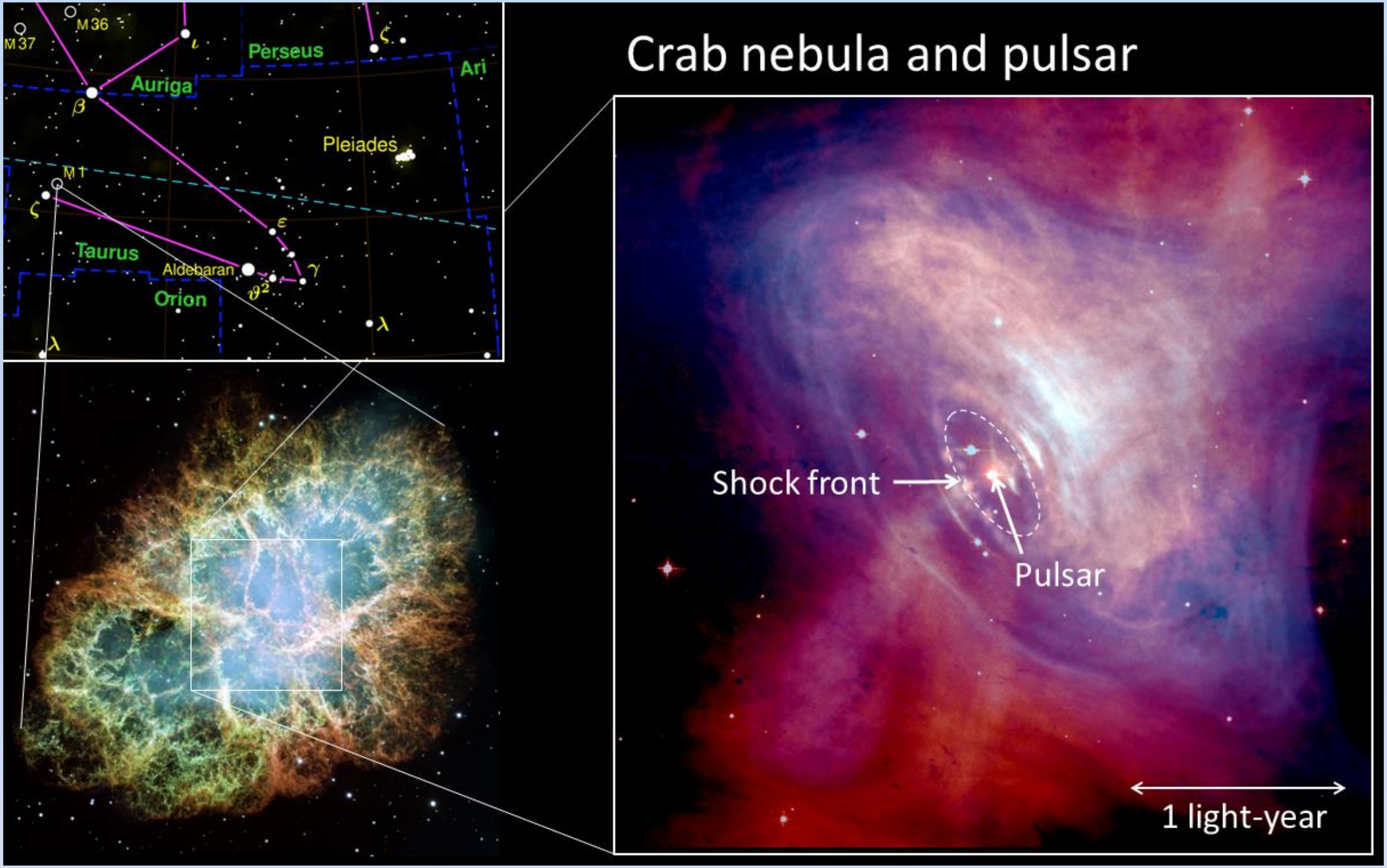
The first pulsar was observed in 1967, period ~1.33 sec

Jocelyn Bell, 1943-

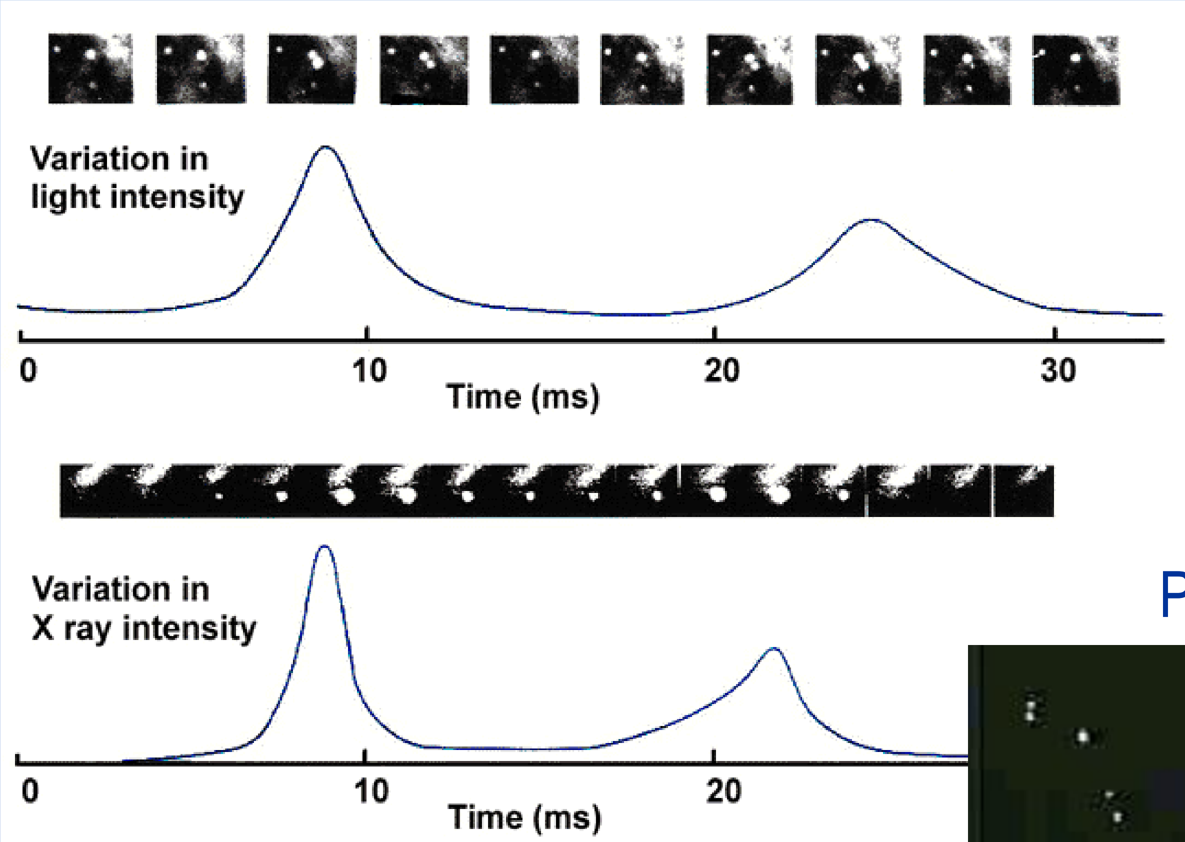
Antony Hewish, 1924-

(Nobel Prize to Ryle and Hewish in 1974.
Somehow without Bell…)

Graphics: MPIK, Image: NASA

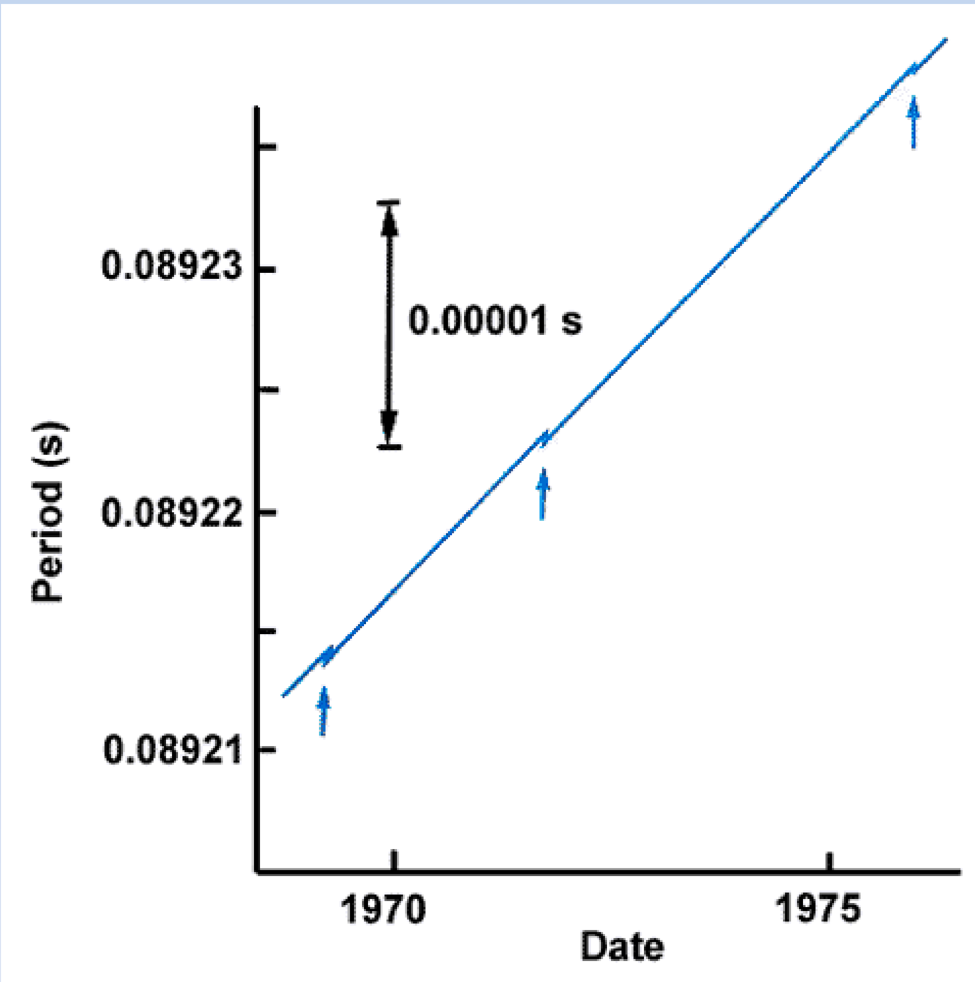


Another example: the pulsar (33-millisecond pulse period) inside Crab Nebula M1, emitting radiations of almost all wavelengths from radio waves to X rays.



Pulsar in Crab Nebula M1

12.3 Pulsars



- ✓ The rotation period of a pulsar can be accurately measured.
- ✓ The rotation of pulsar is decreasing very slowly ! Why?
- ✓ (Partially) because rotational energy is converted into radiation energy.
- ✓ Typically, period P is increasing with a rate of $dP/dt \sim 10^{-15}$

12.3 Pulsars

Example: Crab Nebula

Given: 60 pulses/s, i.e., P = 30 /s and

$dP/dt = 1.3\times10^{-5}$ s yr^{-1}

M = 1.4 solar masses, R =10 km

Rotational K.E. (uniform density)

$$K = \frac{1}{2}I\omega^2 = \frac{1}{2}\left(\frac{2}{5}MR^2\right)\omega^2 = \frac{1}{5}MR^2\omega^2$$

moment of inertia for a sphere

12.3 Pulsars

- Rate of change of K.E. (power lost by radiation)

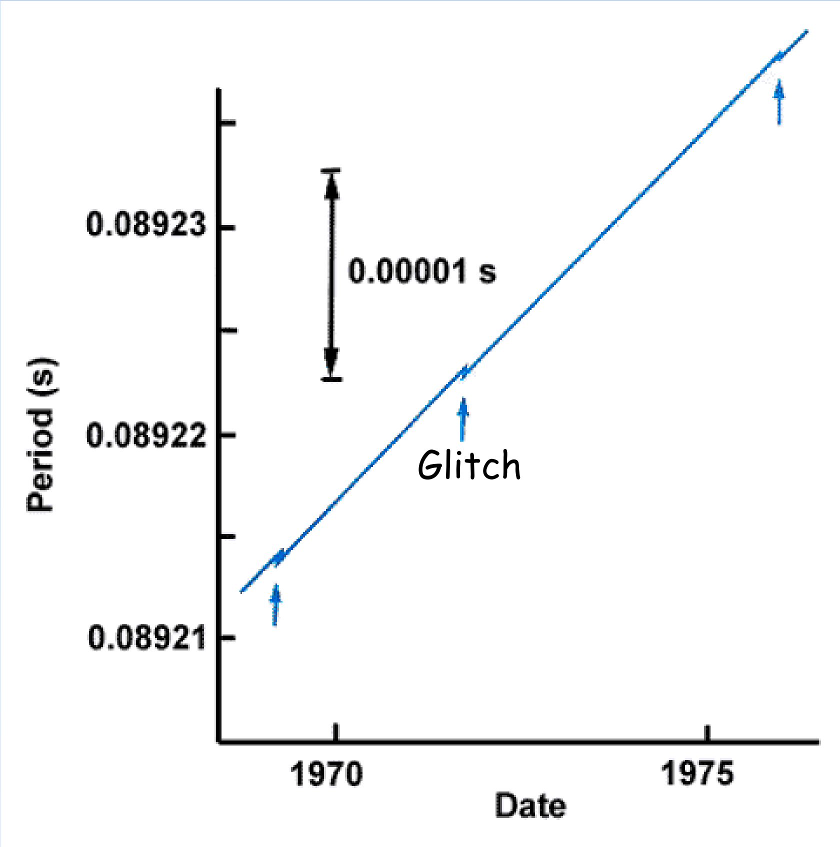
$$\frac{dK}{dt} = I\omega\frac{d\omega}{dt} = \frac{1}{2}I\omega^2 \times \frac{2}{\omega}\frac{d\omega}{dt} = \frac{2K}{\omega}\frac{d\omega}{dt}$$

$$P = 2\pi/\omega \qquad\qquad dP/P = -d\omega/\omega$$

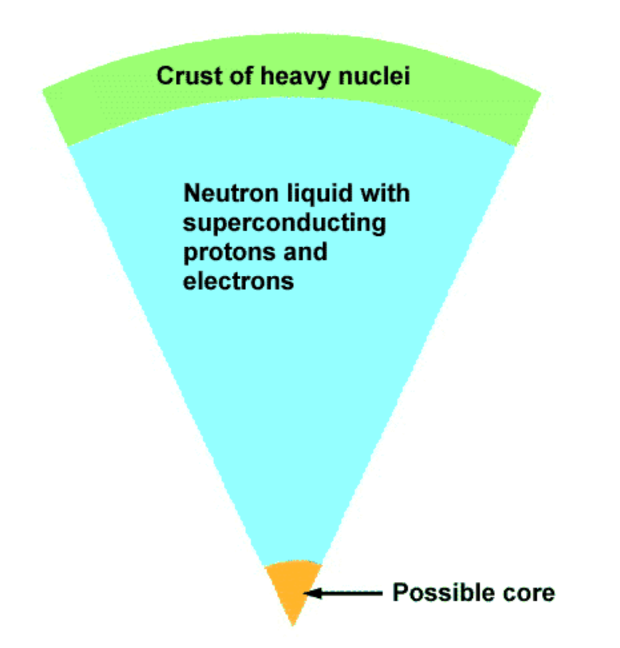
$$\frac{dK}{dt} = -\frac{2K}{P}\frac{dP}{dt} \approx -5\times10^{31}\ \mathrm{W}$$

- ~10^5 times the radiation power of the Sun!

12.3 Pulsars

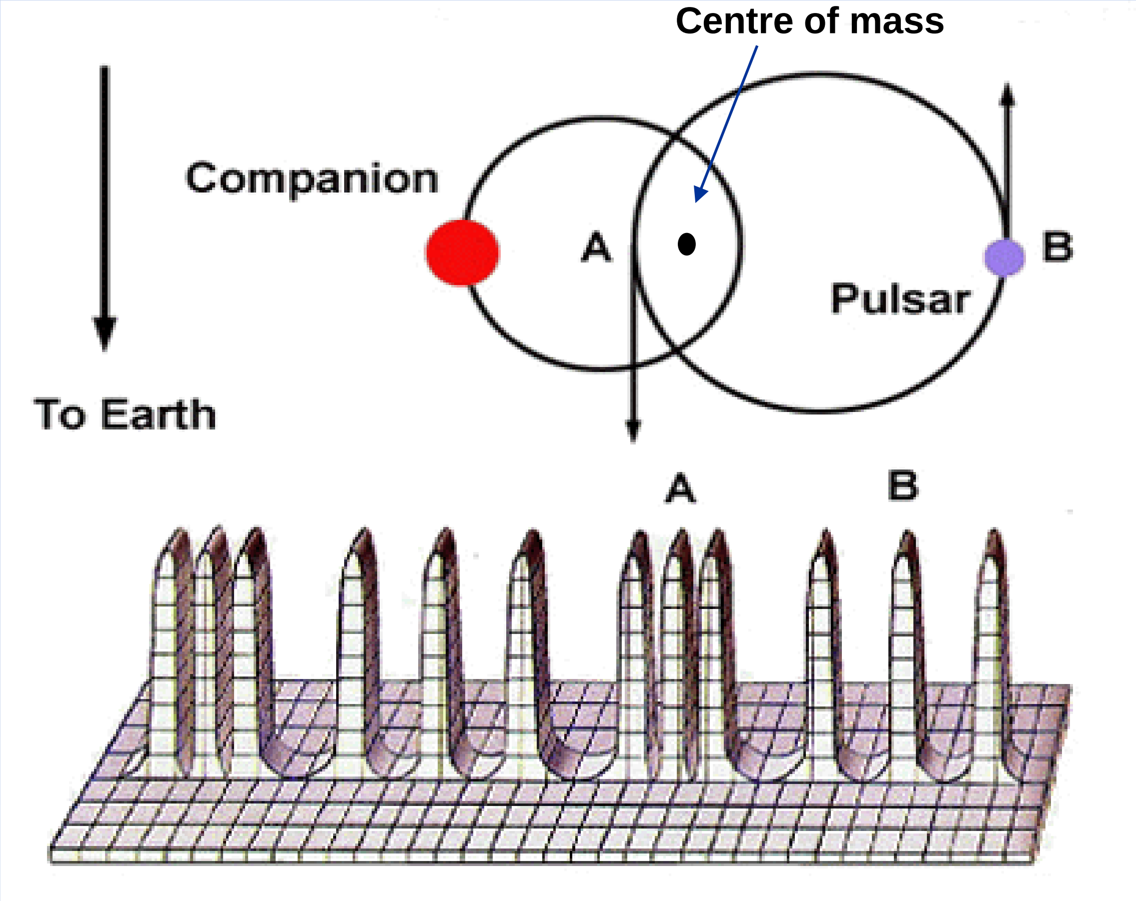


✓ Glitches: Sudden decreases in rotation periods (pulsation periods) of pulsars by very small amounts $|\Delta P|/P \sim 10^{-6}\text{-}10^{-8}$



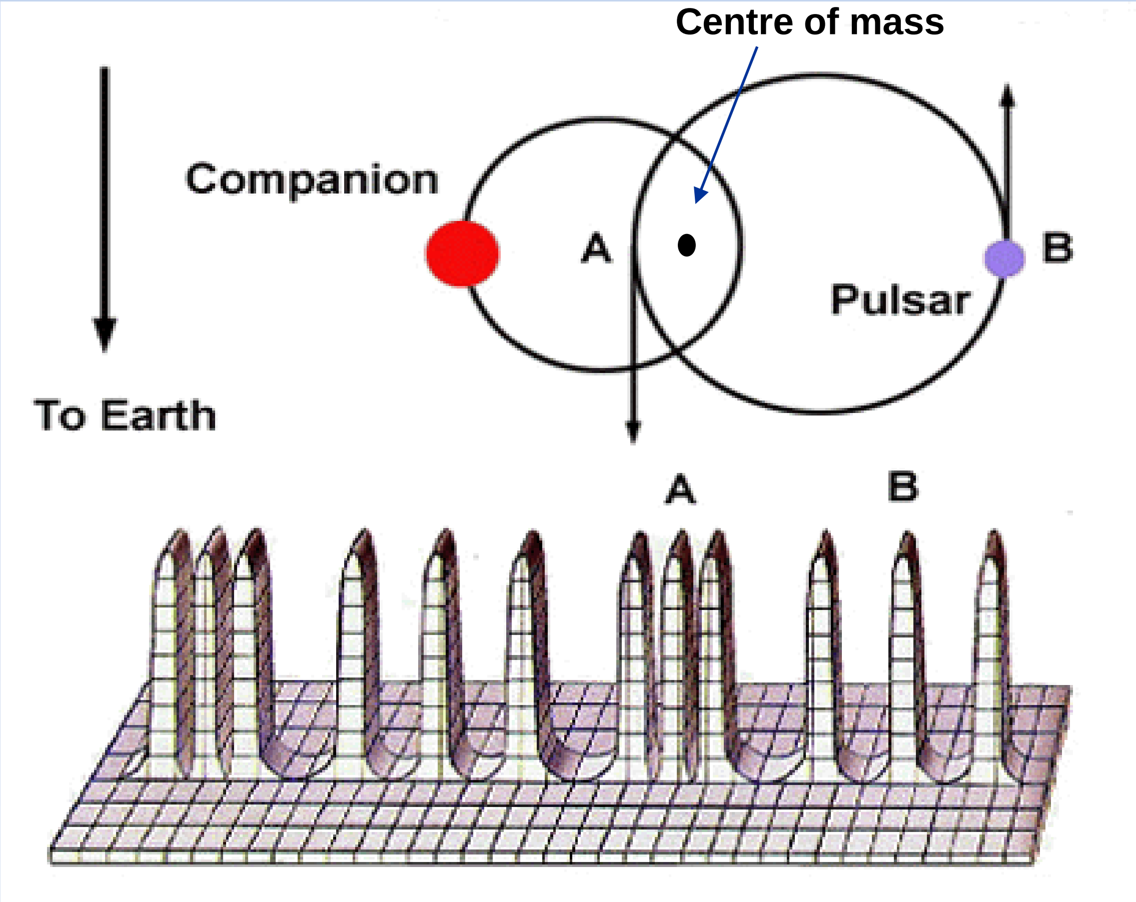
✓ Possible explanation: "star-quakes" - becoming more spherical and spin faster..

12.4 Pulsars in binary systems



- ✓ A binary star system in which one or both components are pulsars.

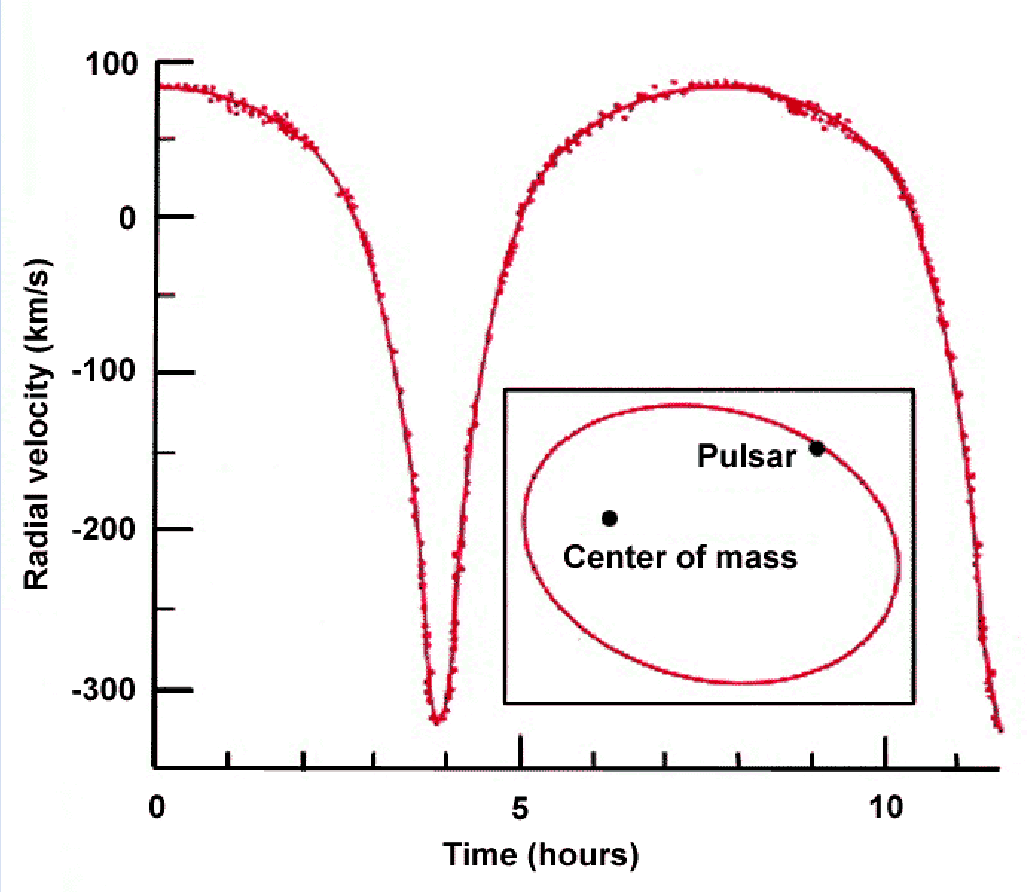
12.4 Pulsars in binary systems



- ✓ As the pulsar is moving in its orbit.
- ✓ The Doppler effect causes its pulsation frequency to *increase* slightly as it is moving towards us (blue shift), and
- ✓ *decrease* slightly as it is moving away from us (red shift)

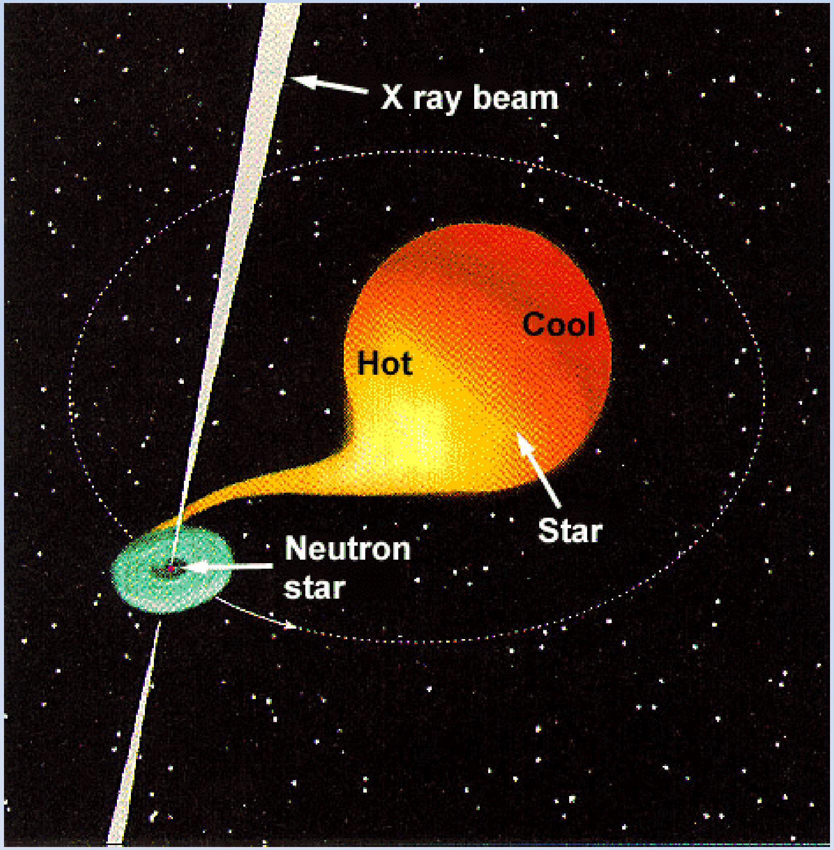
12.4 Pulsars in binary systems

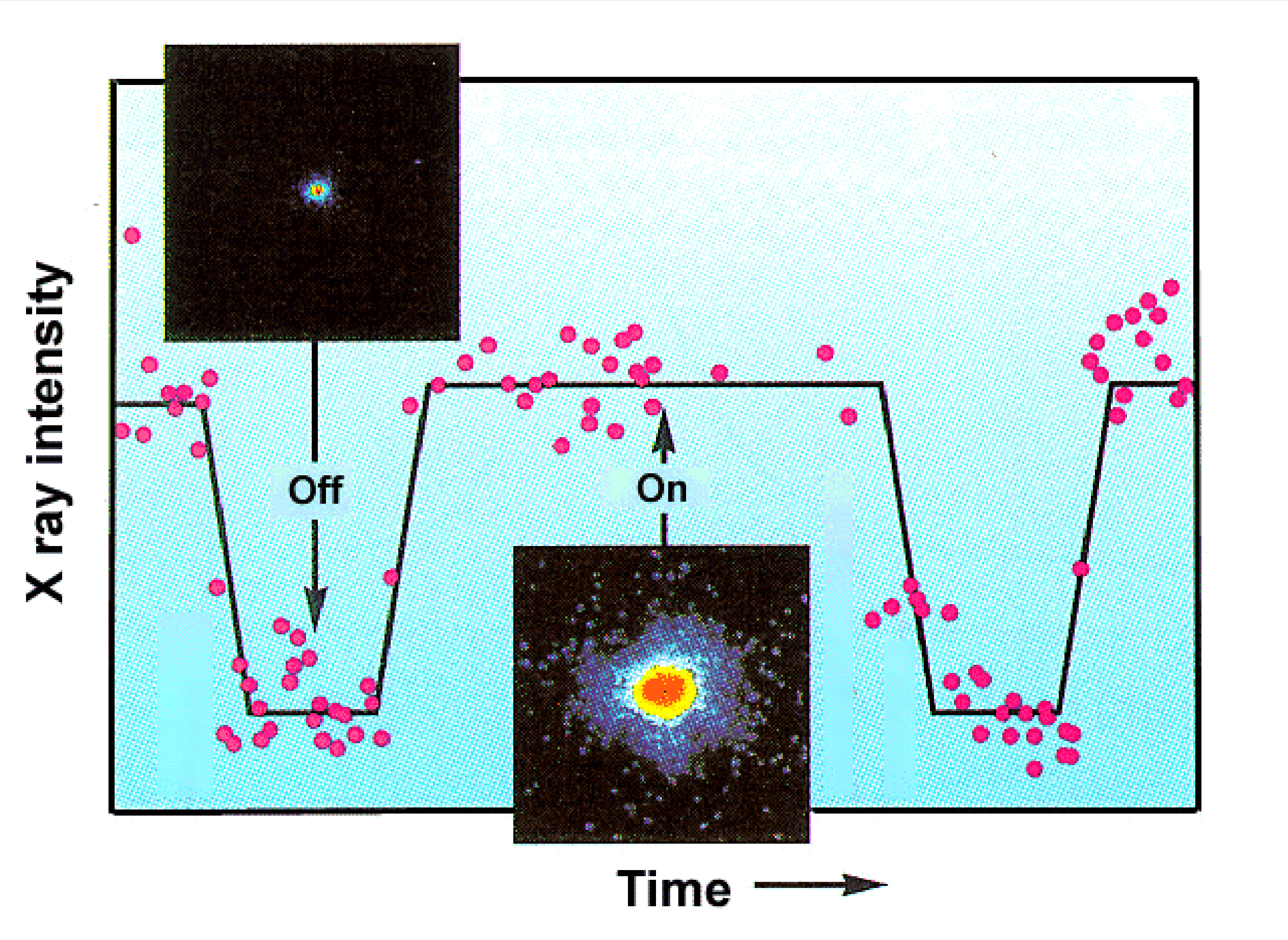
- ✓ The pulsation period is measured to great precision,
- ✓ hence precise knowledge of the orbital motion is obtained.



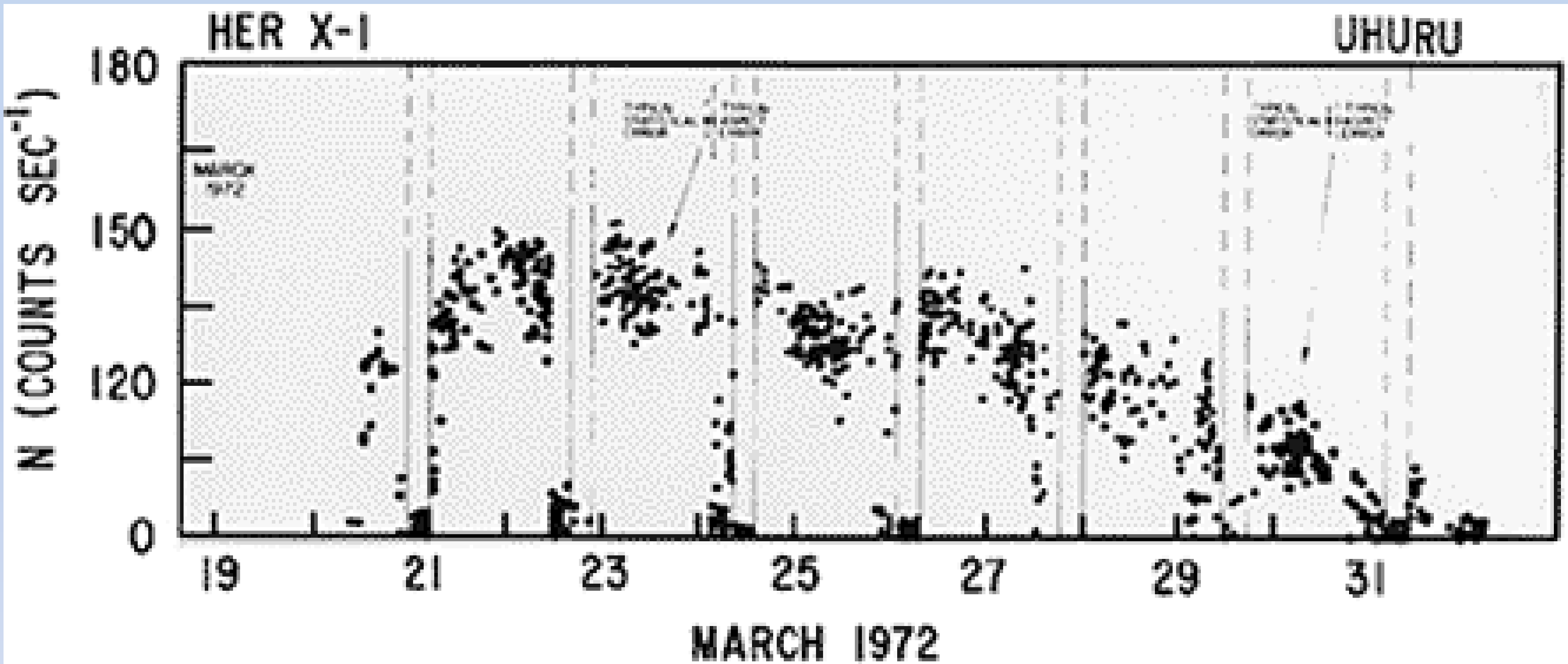
12.4 Pulsars in binary systems

- ✓ In case of class binary, there could be mass transfer from the companion star to the neutron star.
- ✓ An accretion disc is formed.
- ✓ Strong B-field channels the informing matters onto the surface. An violent event with $T \sim 10^{8}\,\mathrm{K}$, enormous amount of radiation emitted, including X-rays and gamma rays

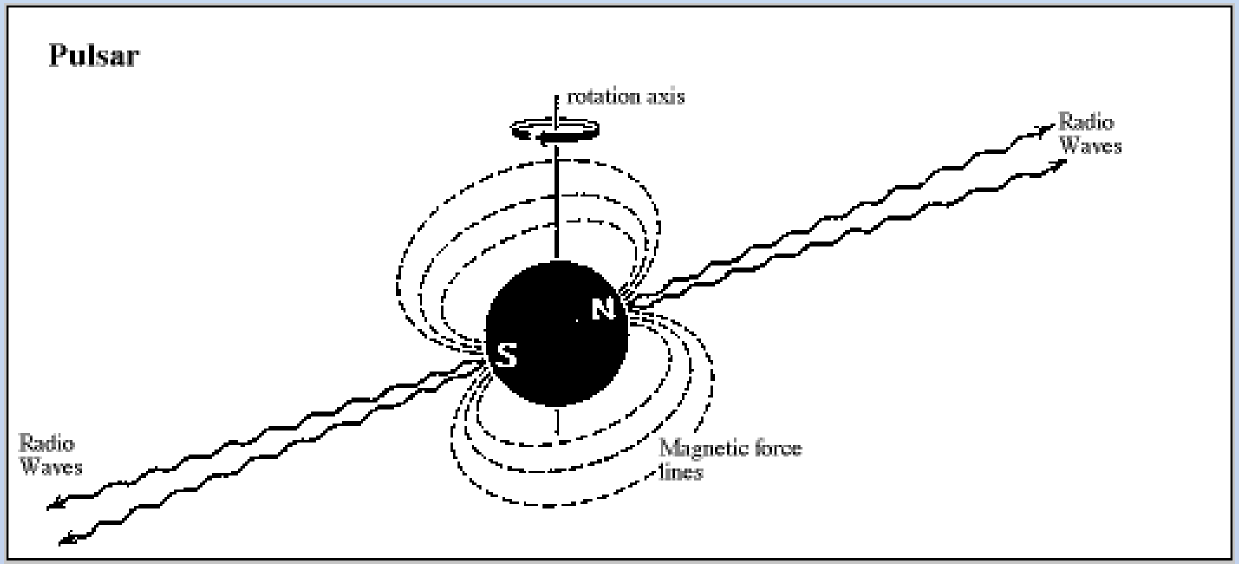


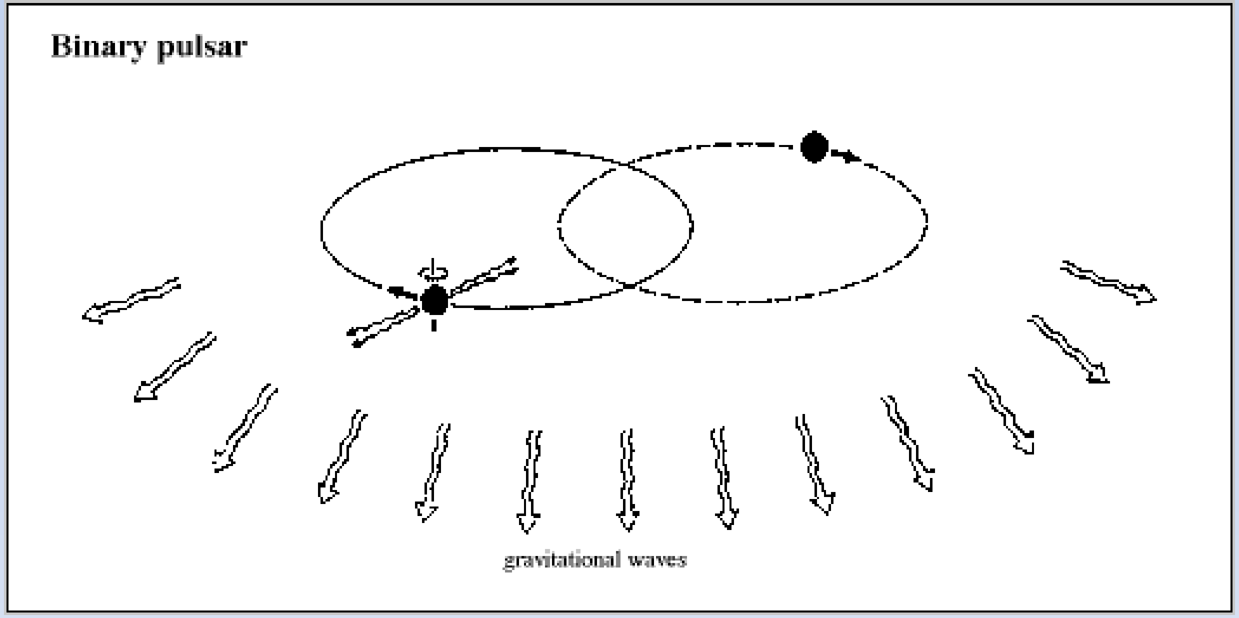


X-ray pulsar Hercules X-1 (武仙座 X-1): companion star *eclipses* the X-ray source periodically.



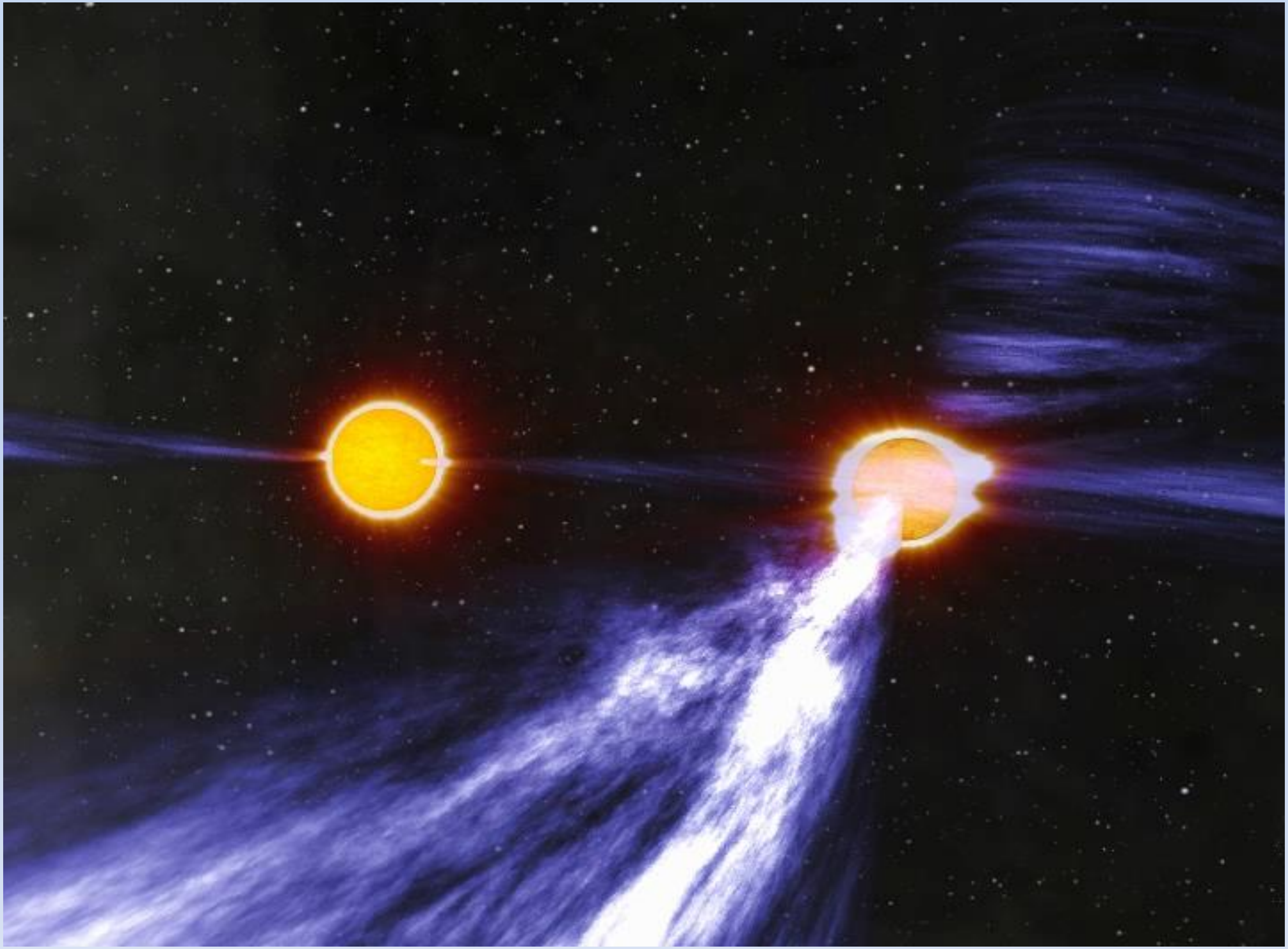
The eclipse of the compact object behind its companion star. This eclipse shows us the orbital period of the system, 1.7 days





PSR 1913+16, a binary system of a pulsar and a neutron star, was discovered in 1974 (Nobel Prize to Hulse and Taylor in 1993). More about it in the next Chapter, when we discuss gravitational wave.

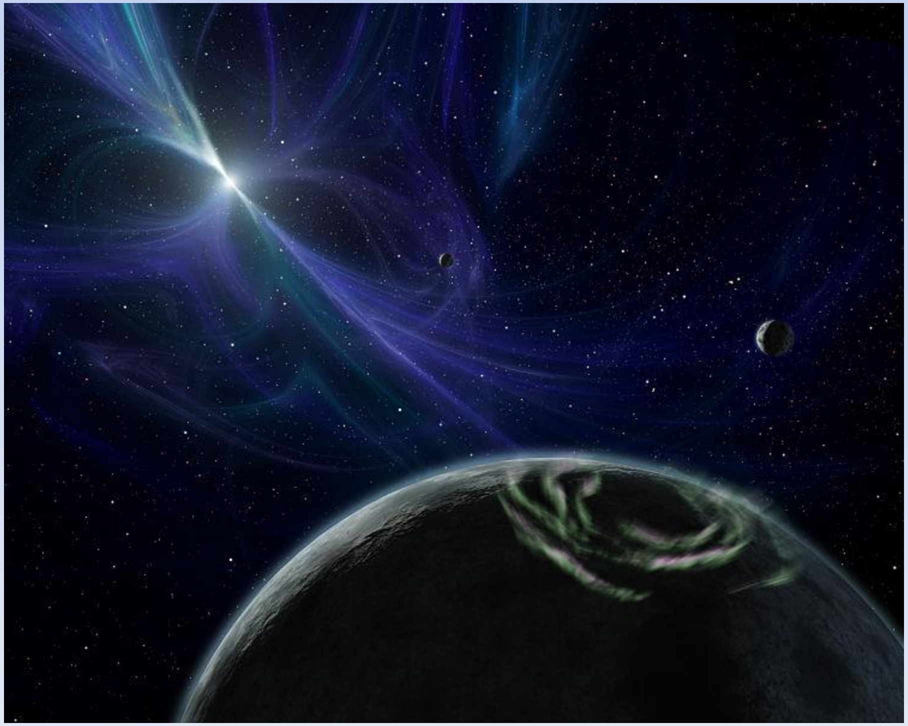
Video: John Rowe Animation/Australia Telescope National Facility, CSIRO



In some rare cases (actually only one known case), two pulsars orbit each other. PSR J0737-3039 is found in 2003.

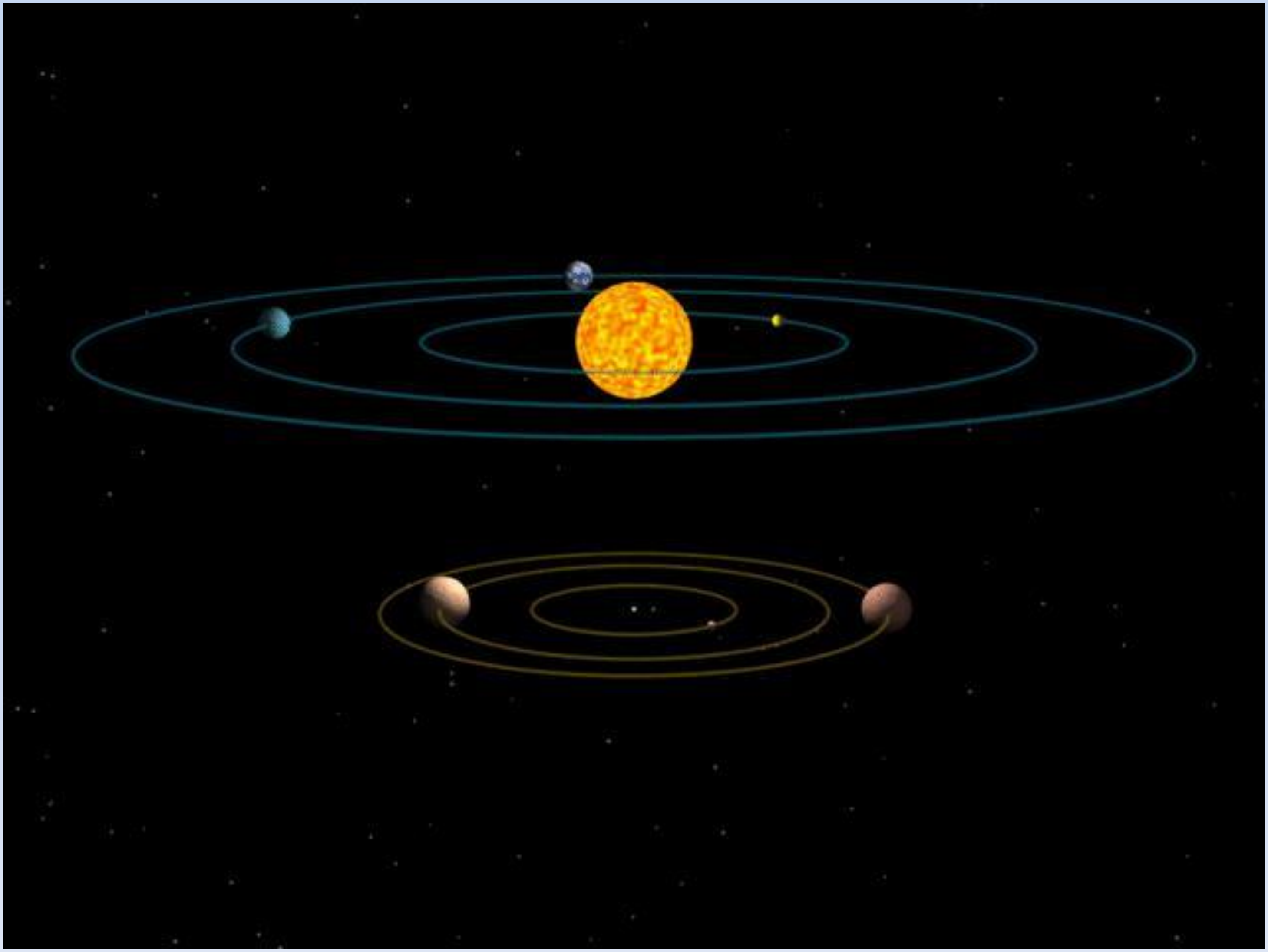
12.5 Planets around a neutron star

- Rotation period of PSR B1257+12 is known to high accuracy (17 digits)
- Small regular modulation of periods agrees well with a theoretical model that three planets orbit the neutron star



Artist's impression of the planets orbiting PSR B1257+12

12.5 Planets around a neutron star



Graphics: astro.psu.edu ; A. Wolszczan

12.5 Planets around a neutron star

- ✓ Somehow the violent environment of a neutron star can also harbor planets!
- ✓ The orbital gravitational interaction between two of the planets are well fitted
- ✓ Planets are indeed very common in the universe!