NEUTRON STARS: PHYSICS IN THE EXTREME

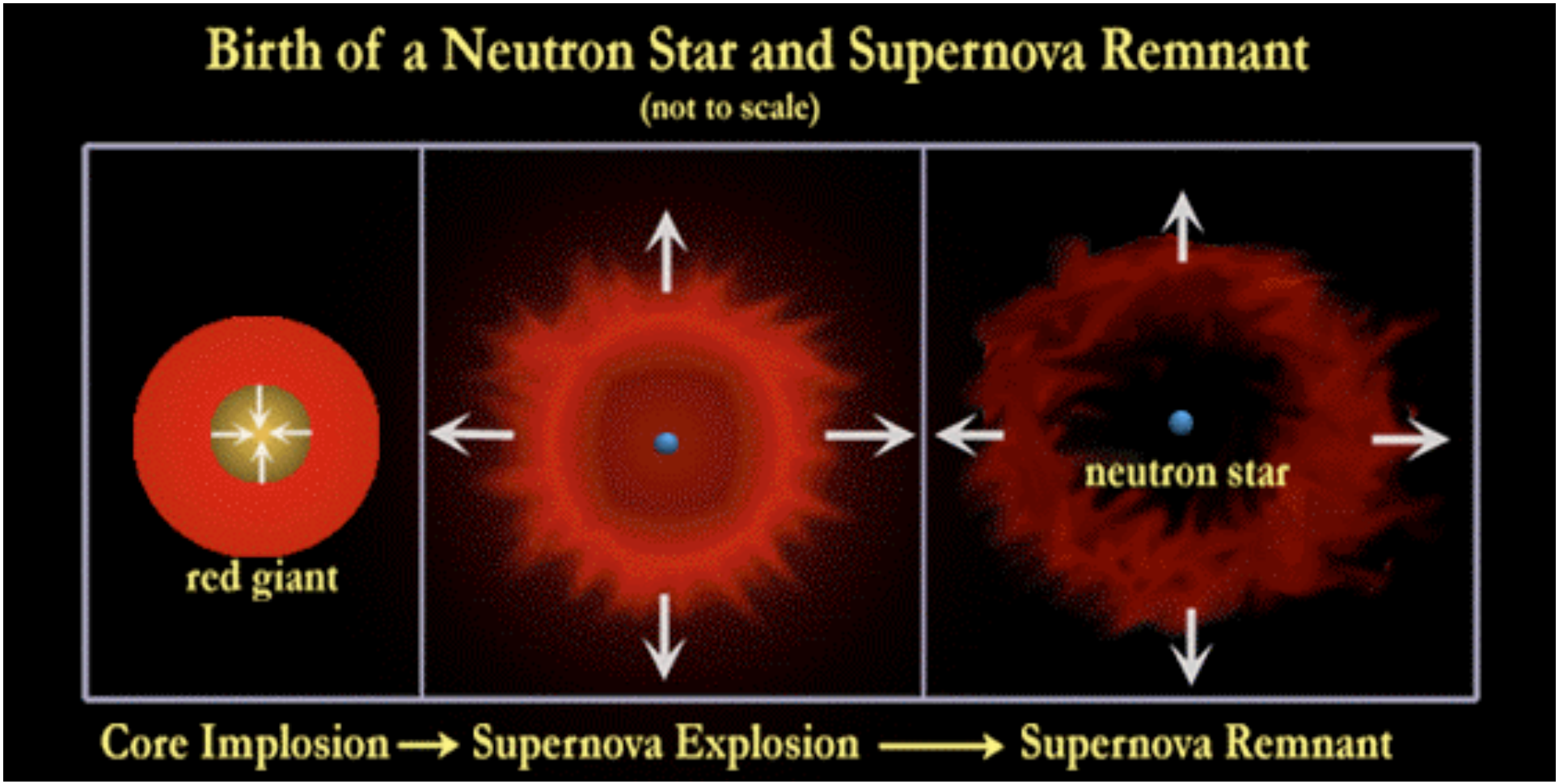
Victoria Kaspi

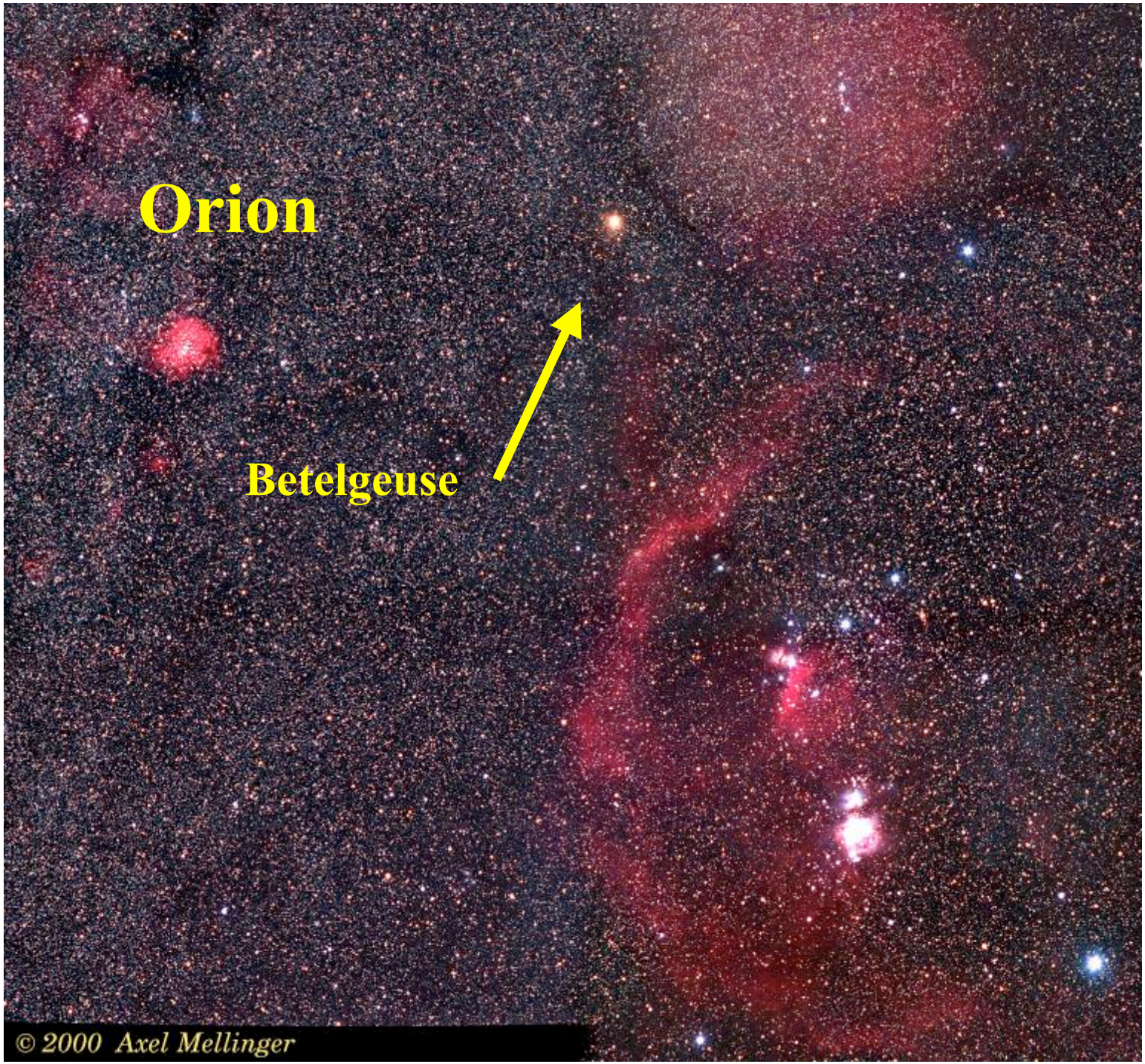
Homer's Physics, Sept 21, 2007

Crab Nebula

- remnant of supernova from 1054 AD
- witnessed by Asian astrologers, recorded
- discovered by Charles Messier in 1758
- hand-sketch looked like a Crab(!)

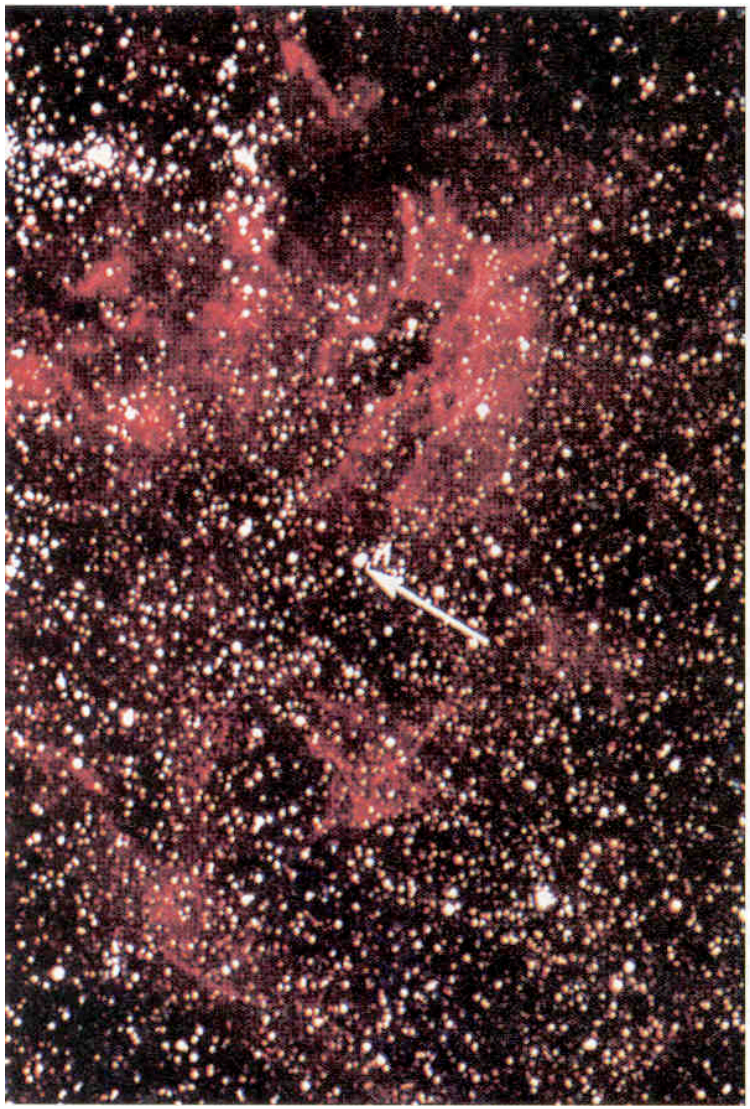
Anasazi Indian cave pictogram, Chaco Canyon, NM


Birth of a Neutron Star and Supernova Remnant
(not to scale)
red giant
neutron star
Core Implosion → Supernova Explosion → Supernova Remnant


Orion
Betelgeuse
© 2000 Axel Mellinger

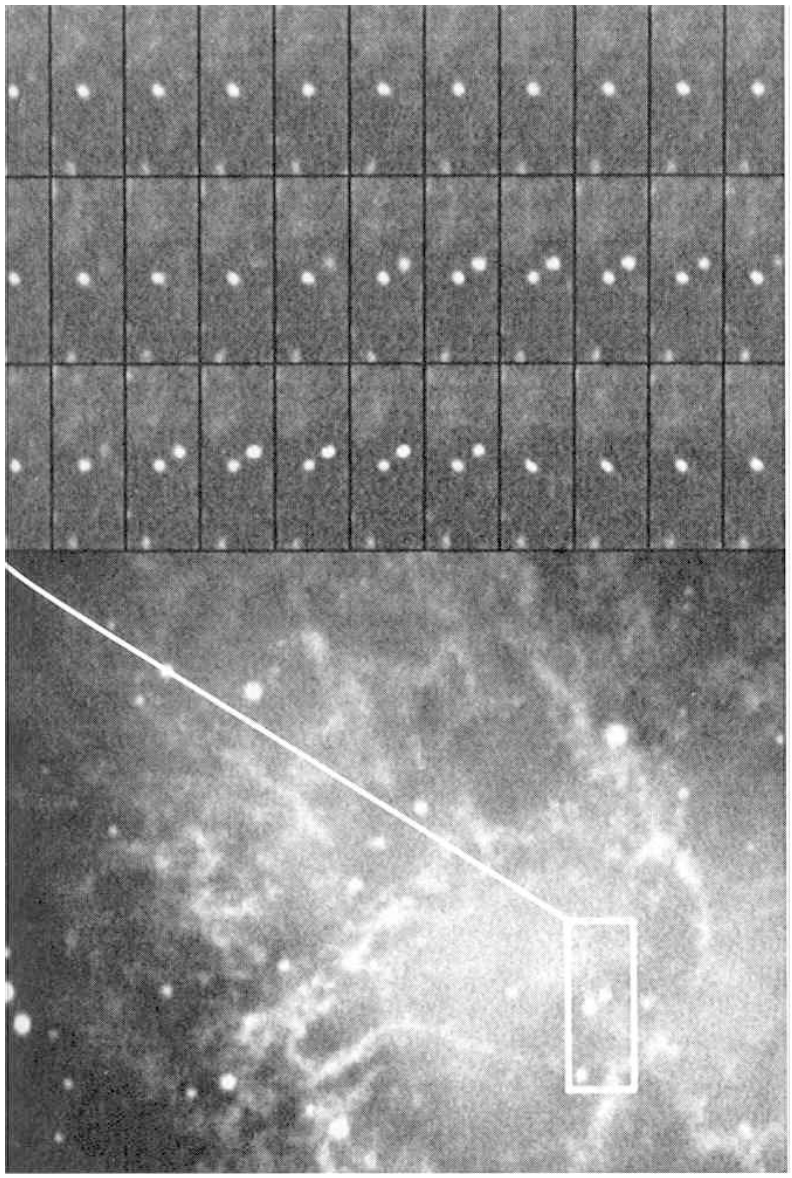
SUPERNOVA 1987A

before Feb 23, 1987



Feb 23, 1987

Crab Nebula



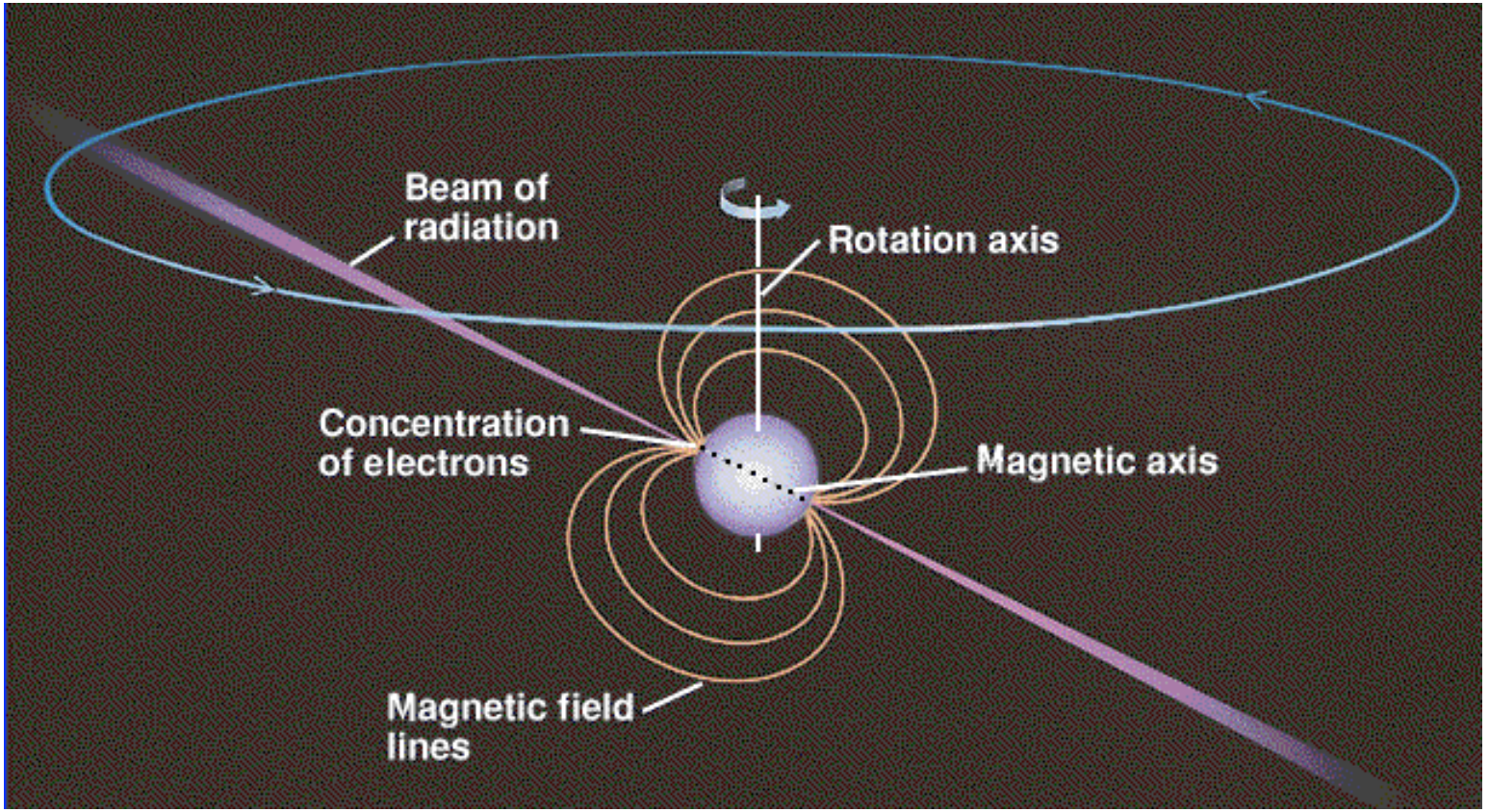
Near centre of Crab
is a neutron star:
a **pulsar.**

The Crab pulsar
pulsates **30 times**
every second!

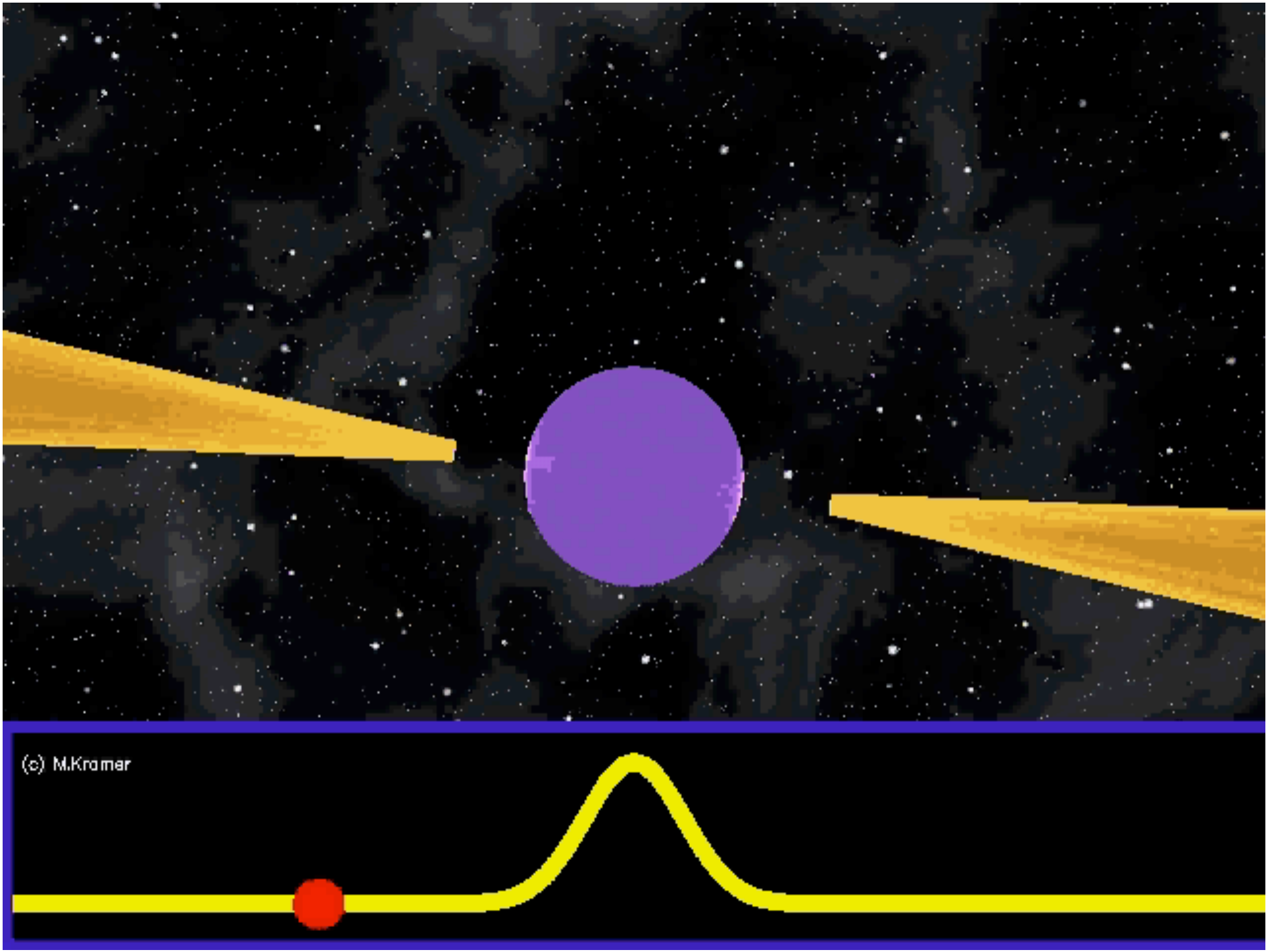
this time sequence lasts
33 milliseconds!

Pulsars

- rapidly rotating, highly magnetized neutron stars



Like a cosmic lighthouse.


(c) M.Kramer

Discovery of Pulsars

Cambridge University graduate student Jocelyn Bell, 1967.

Cambridge U. radio telescope in background.

Discovery of pulsars

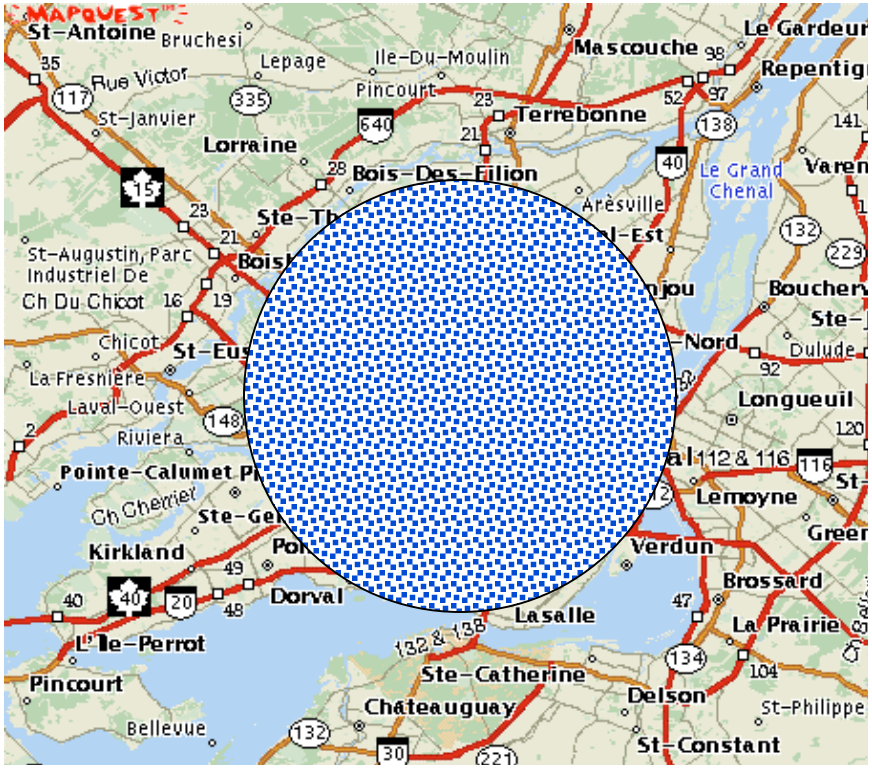
- found by PhD student **Jocelyn Bell**
- group led by Prof. Antony Hewish
  - Jocelyn convinced him of the reality of the signals
- called "**Little Green Men**" initially
  - discovery kept secret for weeks
- found many around the sky
- **Hewish won Nobel Prize in 1974**

Basic Neutron Star Facts

- typical neutron star mass:
  1.4 solar masses
  - about a half-million Earths!
- typical neutron star radius:
  10 km
- fastest known pulsar rotates
  642 times per second!

X

716!



1.4 times the mass of the Sun, crushed into the size of a city, rotating like a household blender!

Pulsar “Sounds”

- ***PSR B0329+54 P=0.7 s***
- ***PSR B0833-45 P=0.089 s***
- ***PSR B0531+21 P=0.033 s***
- ***PSR B1937+21 P=0.0015 s***

Vita-mix 5000:

“fastest blender on Earth”

maxes out at 625 rps

Conservation of Angular Momentum

- skater spins faster as arms pulled in
- same as for collapsing star: initial rotation amplified by collapse

What is the speed at the surface of a millisecond pulsar?

$$v = \frac{2\pi R}{P} = \frac{2\pi 10000}{0.00155} = 4\times10^{7}\, m/s = 0.14c$$

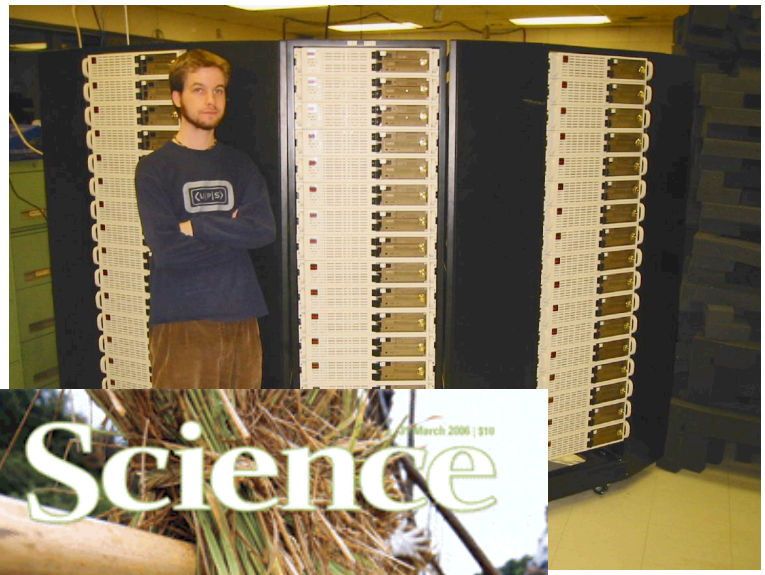
velocity

very fast!

HOW FAST CAN A PULSAR SPIN?

Fastest Pulsar Yet!

- Hessels et al. 2006
- 716 Hz pulsar breaks 23 year old record
- fastest rotating star known
- the search continues…



ASTRONOMY

A Neutron Star in F-sharp

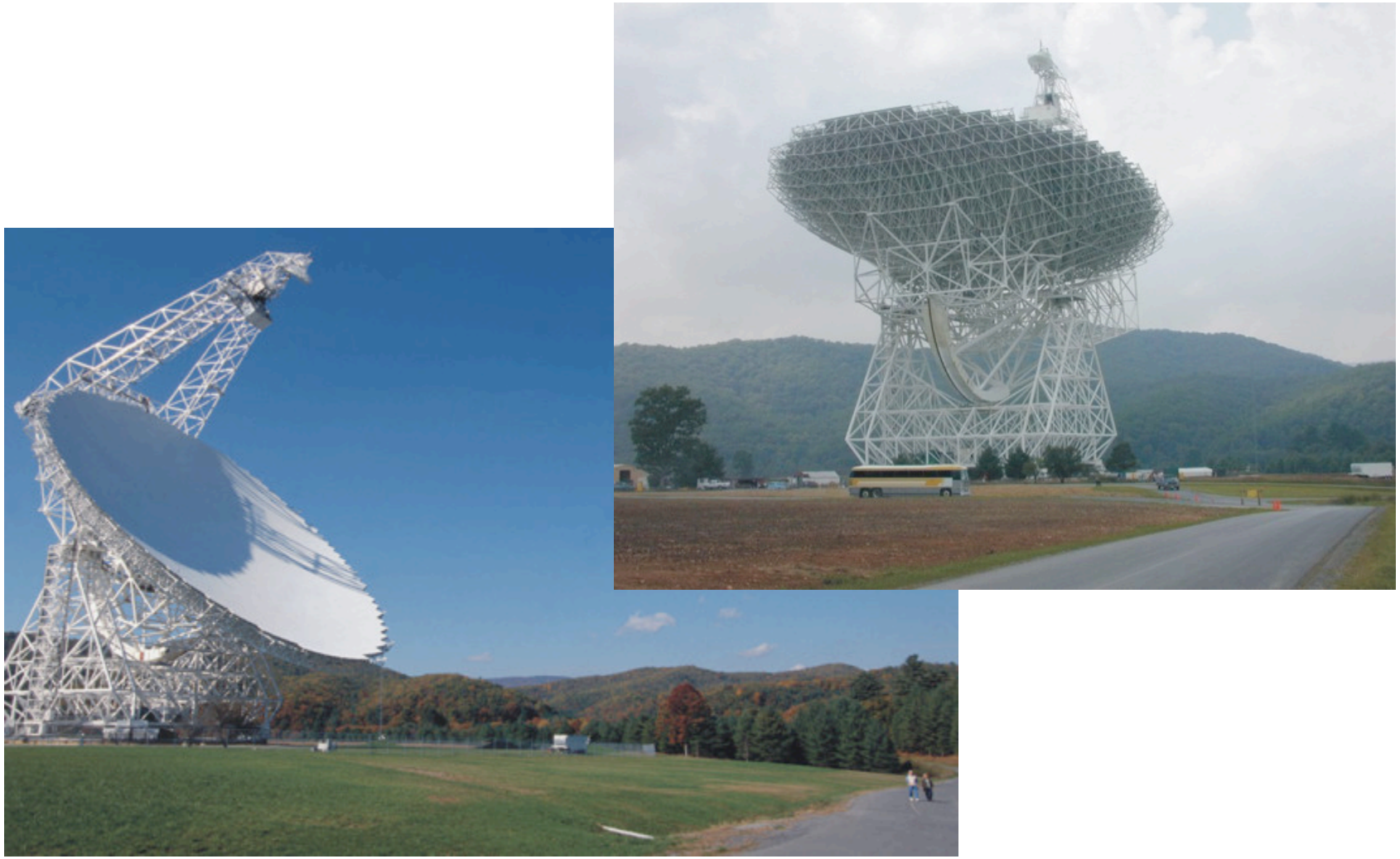
Jonathan E. Grindlay

Millisecond pulsars are extreme examples of what can happen when stars evolve into neutron stars in compact binary systems. These rotating objects are spun up by accretion of matter from their binary companions, producing luminous x-ray emission, and later become detectable as pulsars with periods of a few milliseconds (*1*). As a result, these "fast pulsars" may offer some of the best probes to study matter and space in the relativistic regime of strong gravity. On page 1901, Hessels *et al.* (*2*) report the discovery of pulsar PSR J1748-2446ad in the dense globular cluster Terzan 5 (Ter5-ad). This object, detected with the Green Bank radio

stellar mass or larger
1.396 ms, even shorter
first millisecond pulsa
ms. With a rotation fre
reaches a new high n
celestial spheres—b
whereas B1937+21 (at
between D-sharp and E

Since their discov
been the gateway to
energy at the extreme
stars (*4*). Such stars a
posts of matter and
larger in radius than

100-m Green Bank Telescope in West Virginia



Arecibo Radio Telescope in Puerto Rico

Diameter:
305 m

Pulsars as Physics Laboratories

- **density higher than in atomic nuclei: nature of matter unknown**
  - superb laboratory for studying matter at ultrahigh density: how fast star can rotate depends on internal make-up

Pulsars are Precise Clocks

PSR B1937+21:

P = 1.5578064688197945 ms

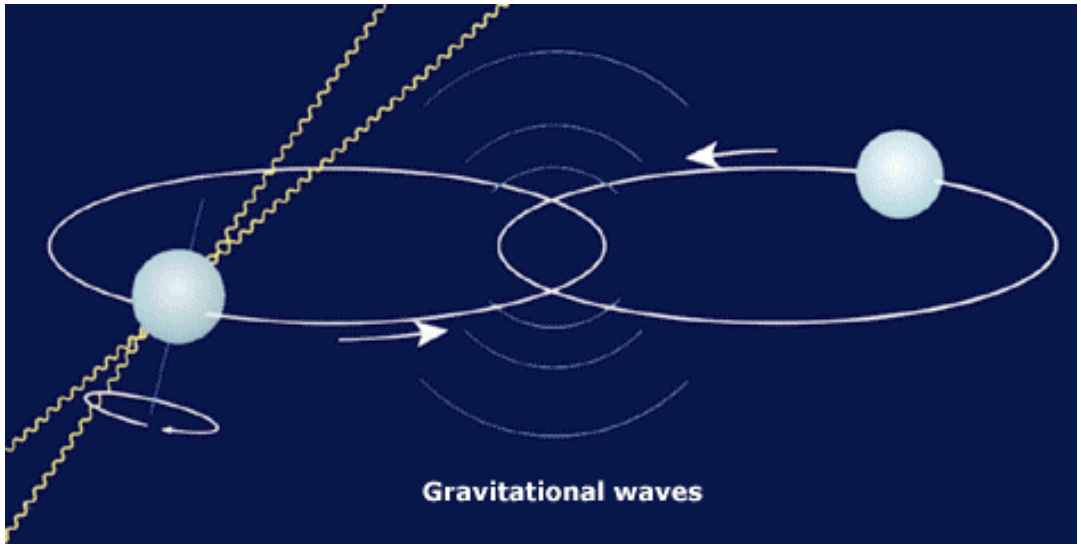
+/- 0.0000000000000004 ms

Pulsars as Physics Laboratories

- **density higher than in atomic nuclei: nature of matter unknown**
  - superb laboratory for studying matter at ultrahigh density: how fast star can rotate depends on internal make-up
- **superb clock-like properties**
  - superb laboratories for studying General Relativity
  - 1993 Nobel Prize in Physics to Hulse & Taylor

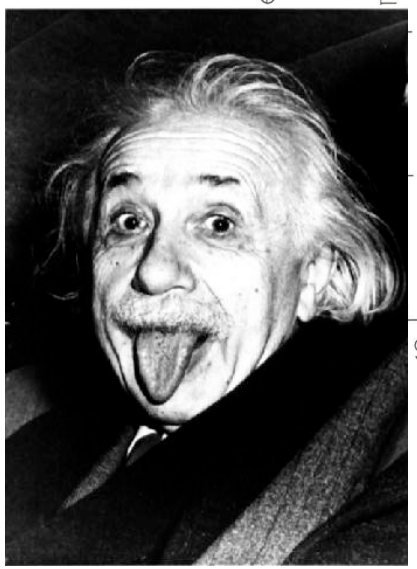
Binary Pulsars

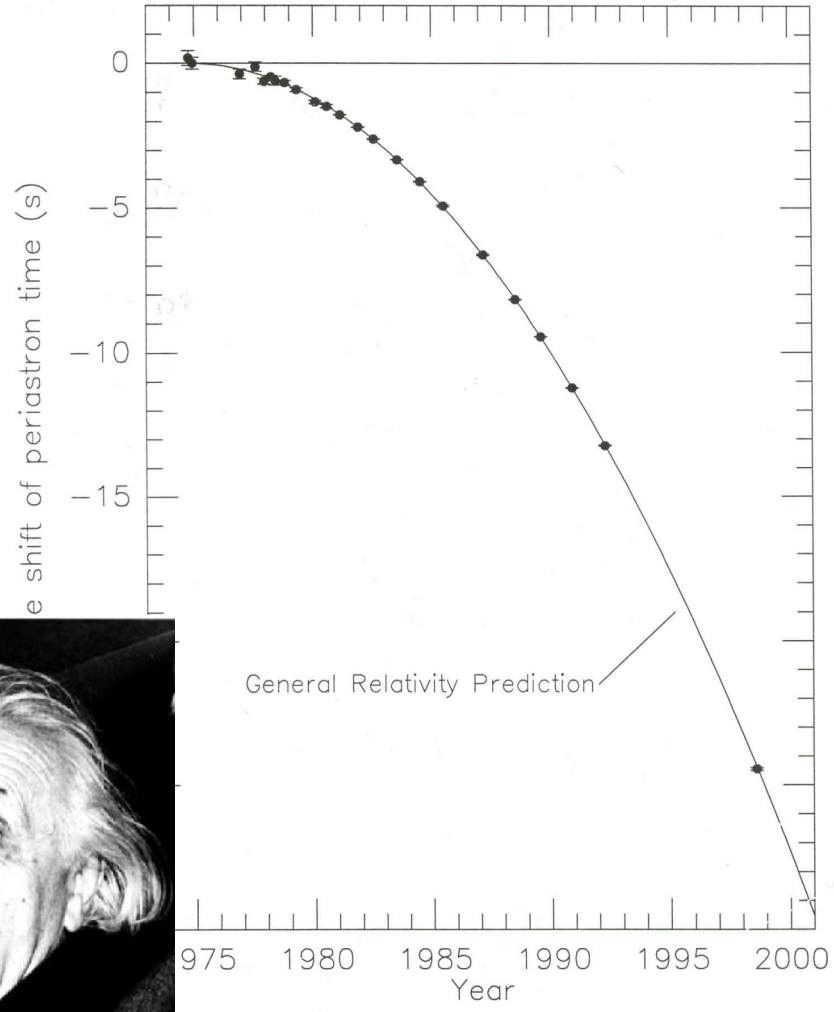
- sometimes find pulsar orbiting another star
- observed from **Doppler shift** of pulsar period
- <u>excellent clock</u>: study orbital dynamics very precisely!



Hulse & Taylor Binary

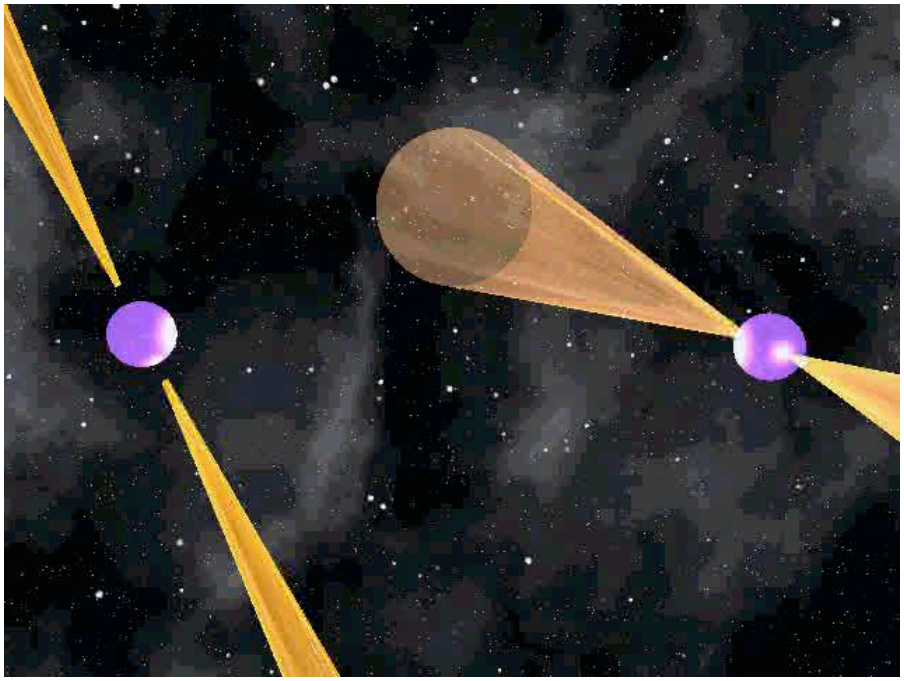
- 2 neutron star orbiting each other every 8 hrs!
- Kepler's laws not good enough here...need General Relativity!
- GR predicts orbit should **decay**
- Nobel Prize 1993 to Hulse and Taylor





2004: Double Binary Pulsar Discovered!

Orbital period: 2.4 hr!

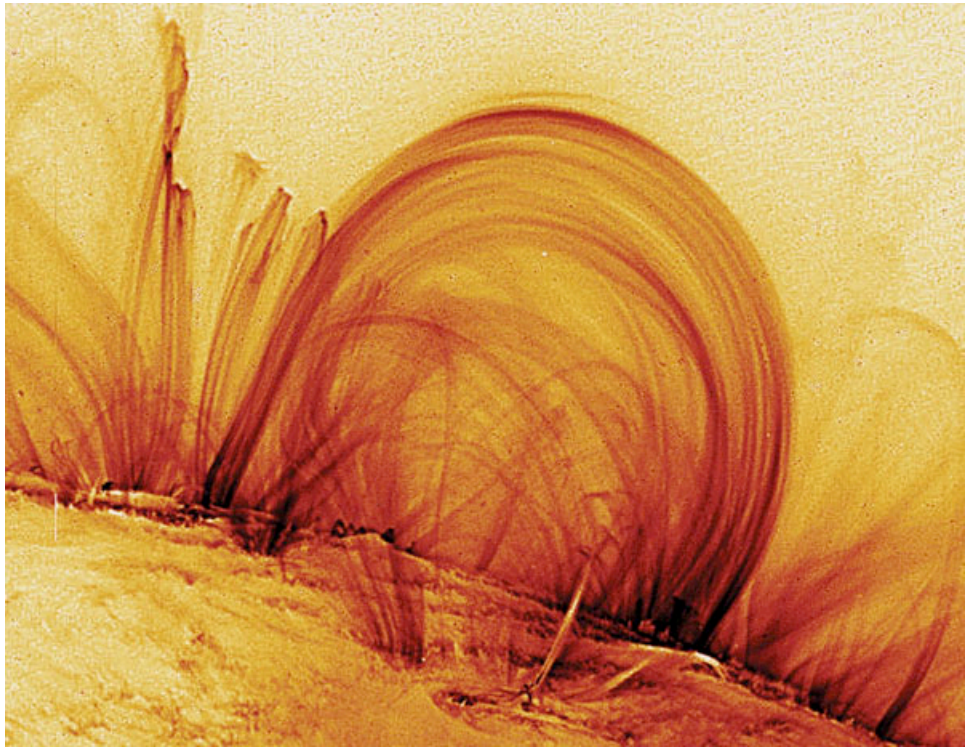


Unprecedented laboratory for testing General Relativity

Magnetars

- **extremely high magnetic field:**
  - **highest known in the Universe**
- Such high fields thought to be unstable inside neutron stars
- Cause stellar crust to crack occasionally: **bursts!**

Stellar Magnetic Fields



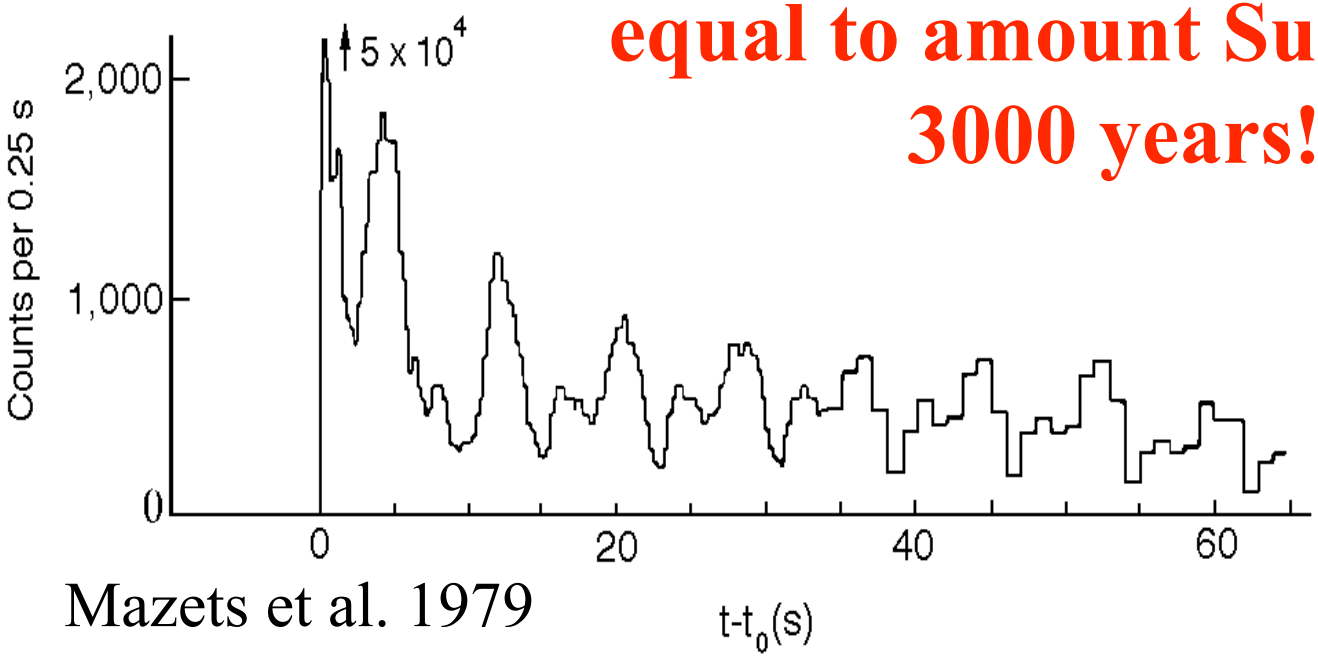
- left is image of the **Sun** made with NASA's TRACE mission
- loops of hot plasma trace out solar **magnetic fields**
- source of **solar flares**, prominences
- solar magnetic field ~100 times larger than that on Earth

MAGNETAR FIELD ~10 QUADRILLION TIMES LARGER!

Magnetar: artist's depiction

March 5, 1979: SGR 0526-66

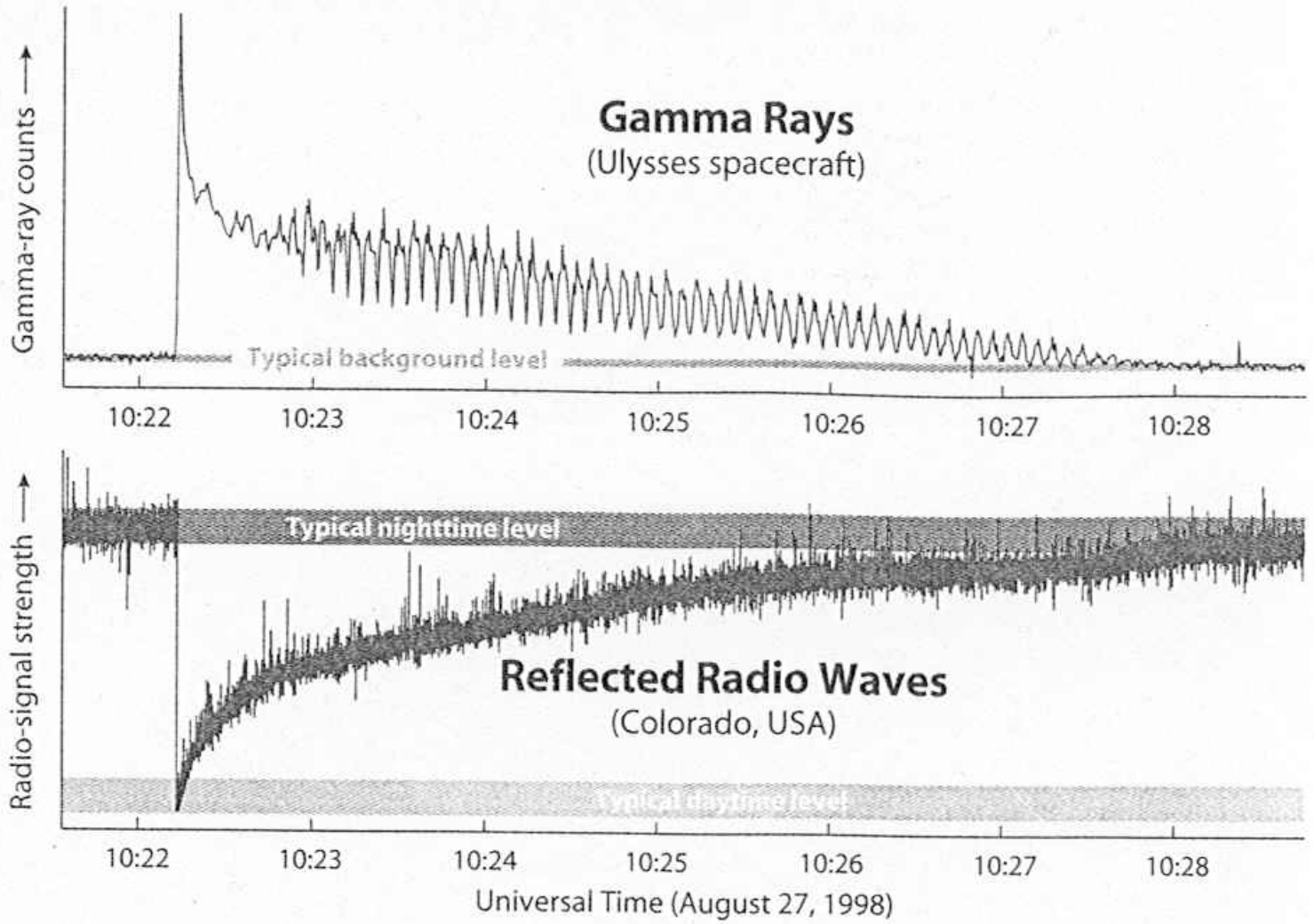
total energy released in 1 minute equal to amount Sun releases in 3000 years!



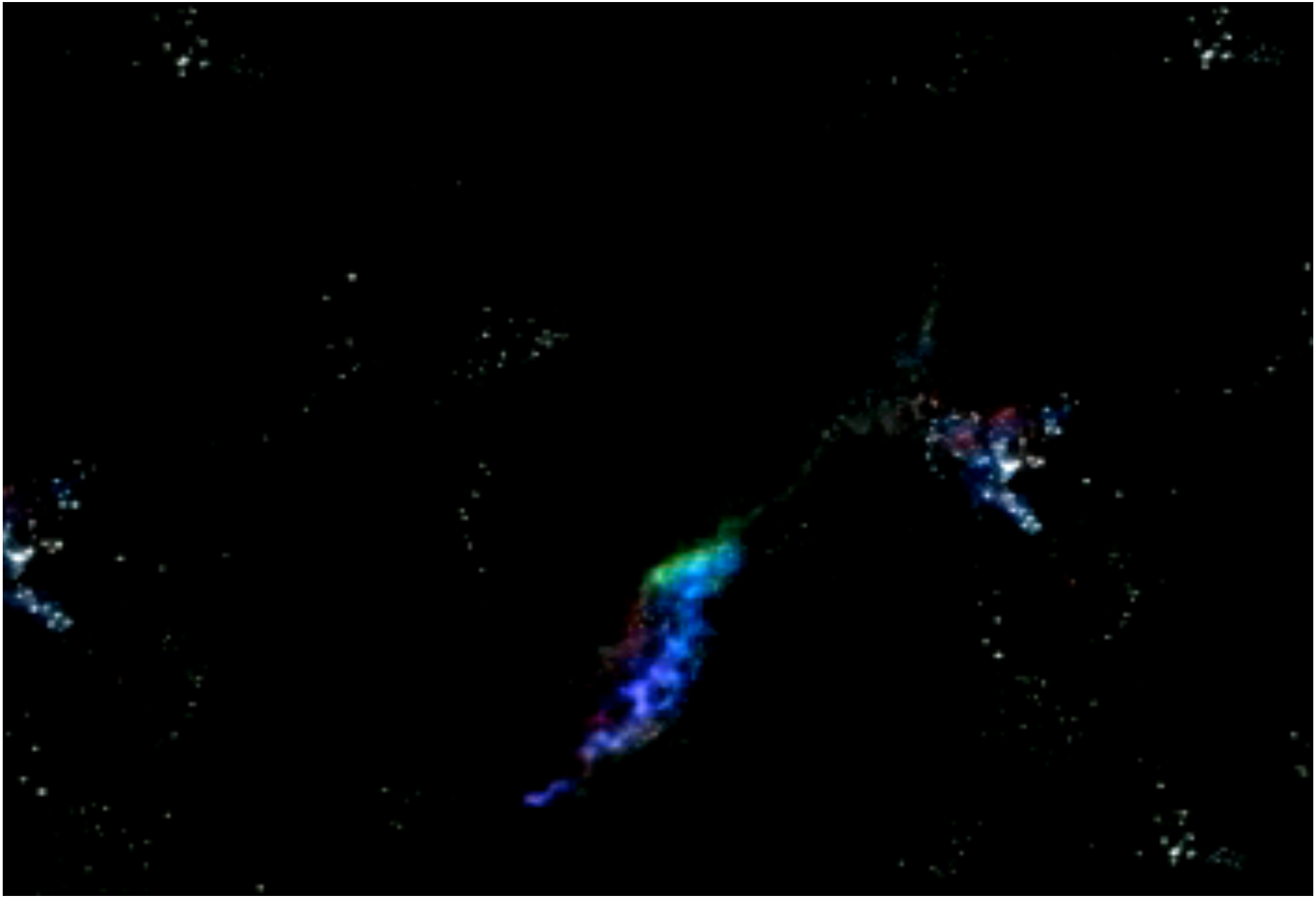
Mazets et al. 1979

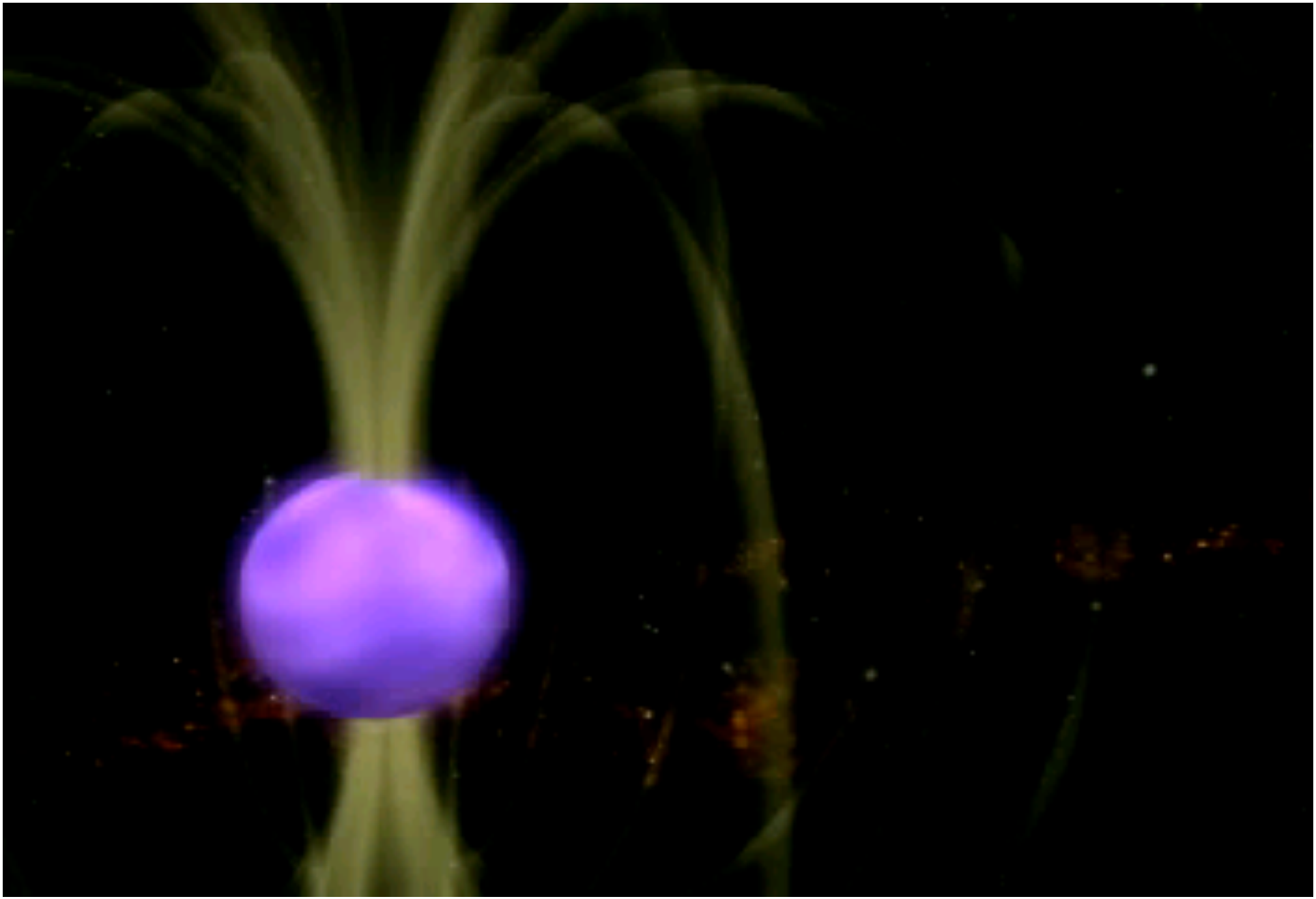
gamma rays

From supernova remnant N49 in LMC



Blast from the past. High-energy photons erupted from a neutron star in Aquila roughly 20,000 years ago, only to smash into Earth last August. They then bloated our ionosphere, temporarily weakening radio transmissions that travel from Hawaii to Colorado and are reflected by the ionosphere en route. Courtesy Michael Johnson, Stanford University.





X-ray Astronomy

NASA's
Rossi X-ray Timing Explorer

NASA's Chandra X-ray Observatory

ESA's XMM-Newton Observatory

McGill Pulsar Research Summary

- We search for and study unusual pulsars:
  - **Millisecond pulsars**
    - Constrain nature of matter at ultrahigh densities by finding a sub-millisecond pulsar!
  - **Binary pulsars**
    - Test Einstein's Theory of General Relativity
    - Find a pulsar-black hole binary??
  - **Magnetars**
    - Study nature of matter in ultra-high magnetic fields

McGill Pulsar Group