

The Secret Life of Neutron Stars

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Harvard-Smithsonian CfA

Supernova Remnants



SN1987a - 15 yr

Cas A - 323 yr

Crab - 948 yr

G292.0+1.8 - 1600 yr

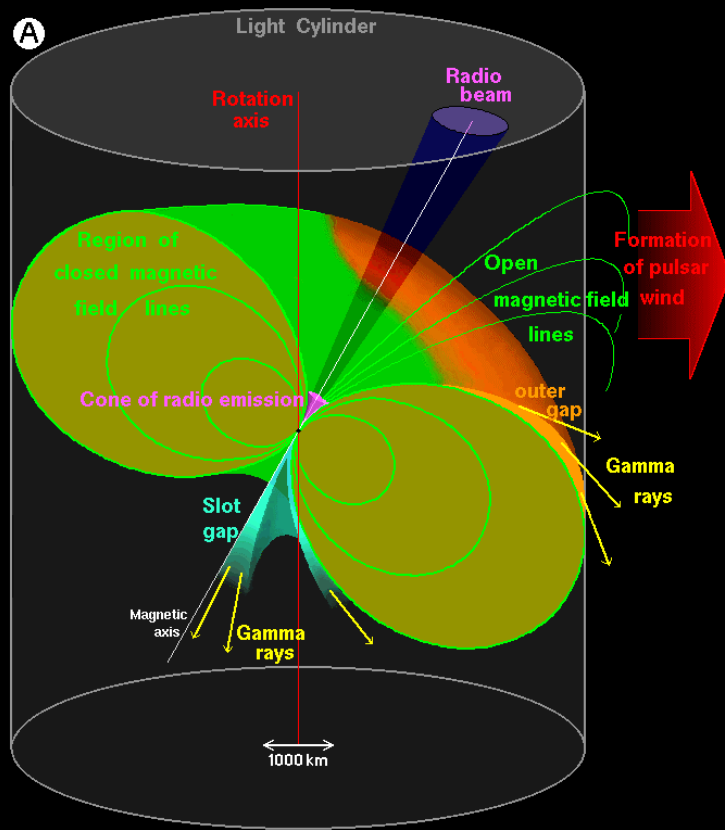
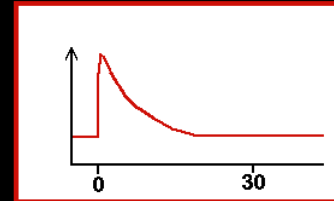
Cygnus - 5-10 kyr

Vela - 12-20 kyr

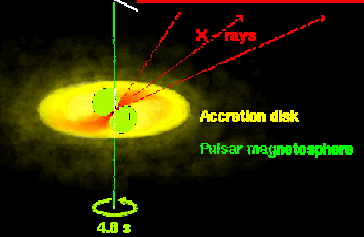
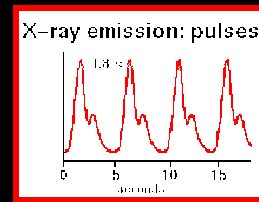
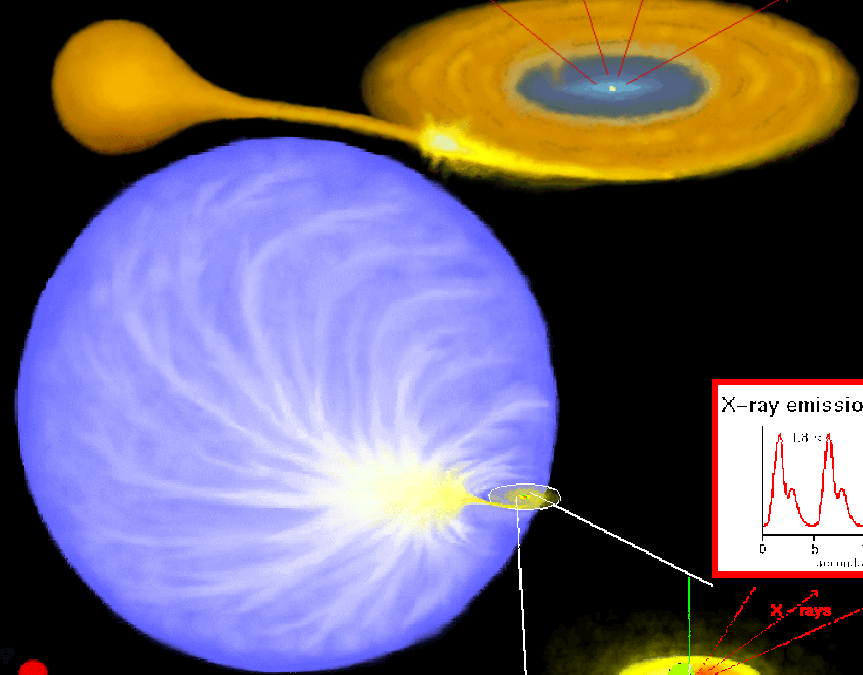
Monogem - 0.1 Myr

Noah & Jonah - 6 Gyr

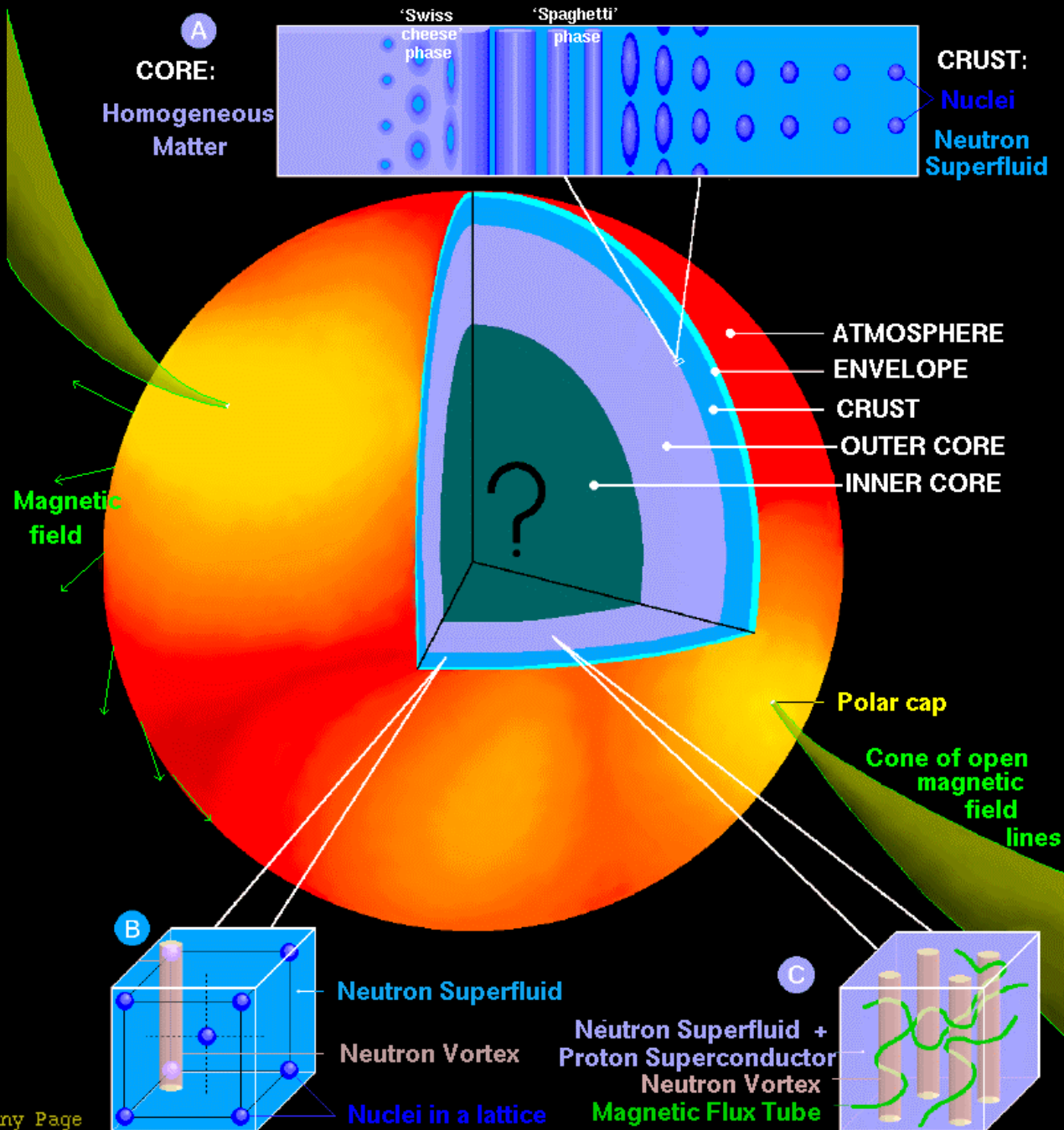
Neutron Star Gallery



Formation of pulsar wind

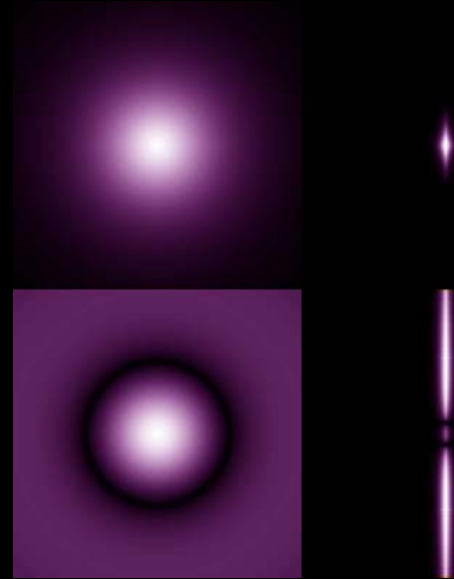


A NEUTRON STAR: SURFACE and INTERIOR

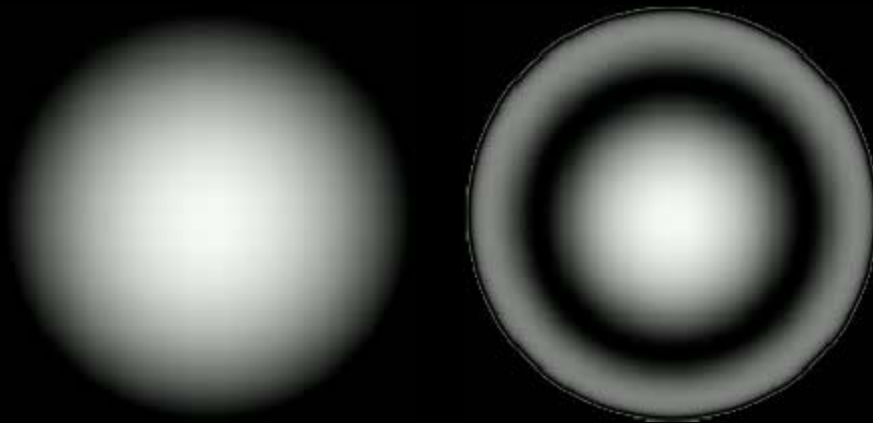




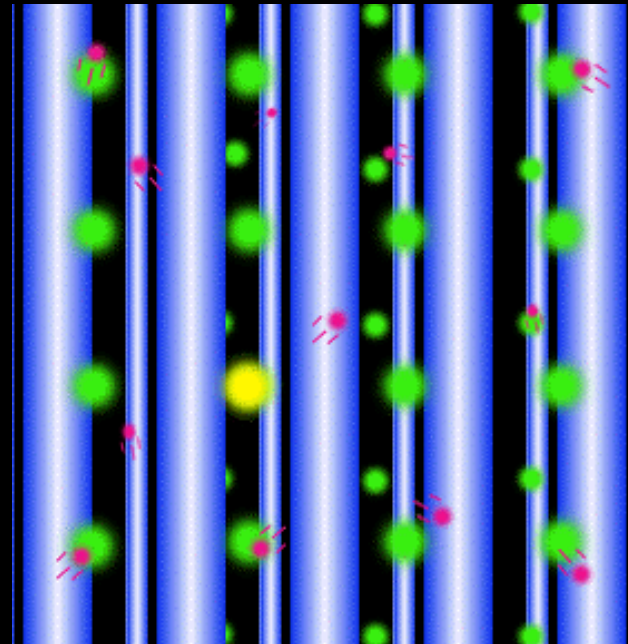
MAGNETOSPHERE: Magnetic Lensing



ATMOSPHERE: Magnetic Atoms



MAGNETOSPHERE: Gravitational Lensing



ENVELOPE: Anisotropic Heat Conduction

Young Neutron Stars

◆ Sources of energy:

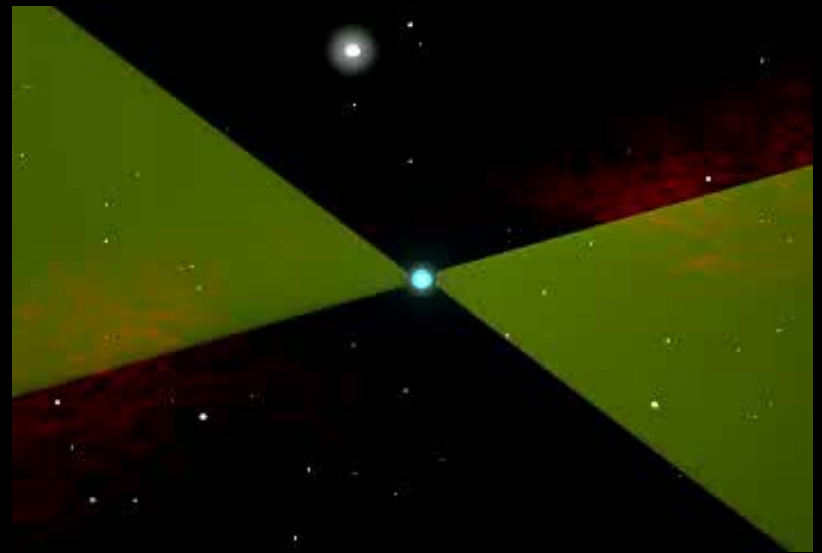
- spin: few NS are born near break-up
- heat: every NS starts at 10^9 K but may cool quickly in 10^{2-3} yr.
- magnetic field: typical radio pulsars have $\sim 10^{11-13}$ G, but typical NS may have stronger fields.

◆ Tapping the energy:

- magnetic dipole radiation v. gravitational waves
- photons v. neutrinos
- ambipolar diffusion v. magnetic reconnection

Young Radio Pulsars

- ◆ Are radio pulsars typical young neutron stars?
- ◆ Is the Crab pulsar the prototypical young radio pulsar?



But they aren't all Crabs...

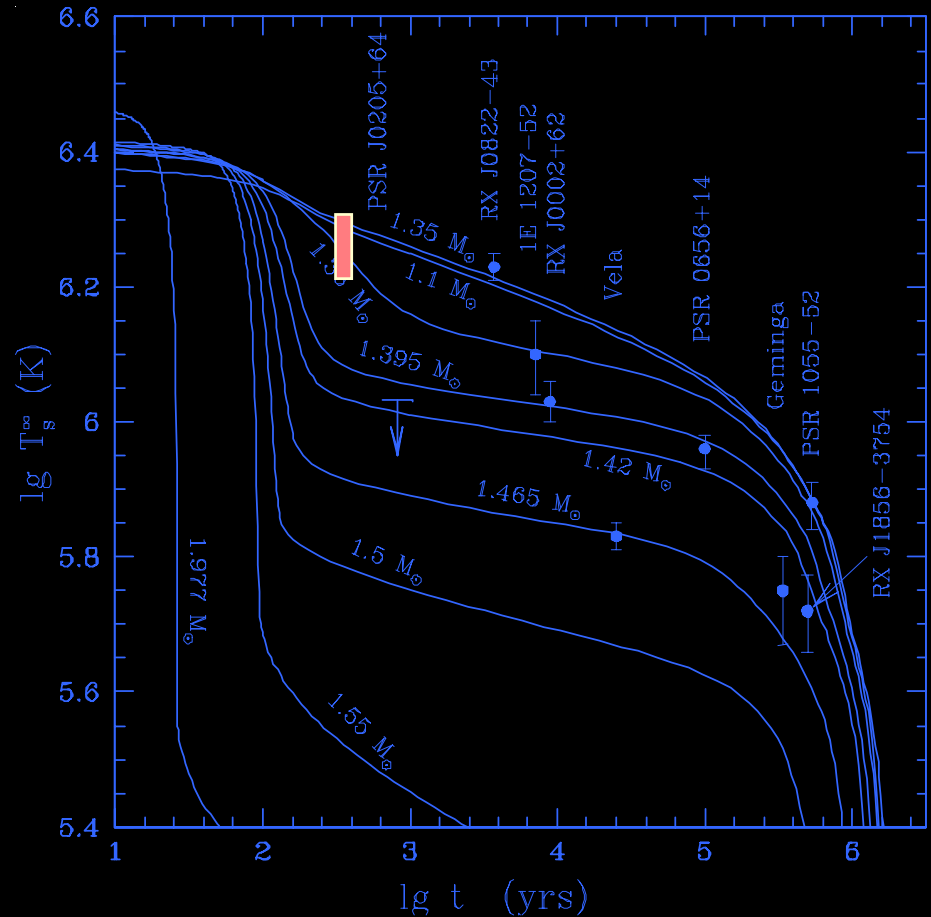
Evidence	Plerionic Remnant	Composite Remnant	Pure Shell Remnant
Pulsar + Supernova Remnant (15+2)	G106.6+2.9 [PSR J2229+6114] G130.7+3.1 (3C 58) [PSR J0205+64] G184.6-5.8 (Crab) [PSR B0531+21] N157B (in LMC) [PSR J0537-6917]	G5.4-1.2 (Duck) [PSR B1757-24] G11.2-0.3 [PSR J1811-1925] G29.7-0.3 (Kes 75) [PSR J1846-0258] G34.7-0.4 (W44) [PSR B1853+01] G69.0+2.7 (CTB 80) [PSR B1951+32] G114.3+0.3 [PSR B2334+61] G263.9-3.3 (Vela) [PSR B0833-45] G292.0+1.8 [PSR J1124-5916] G308.8-0.1 [PSR J1341-6220] G320.4-1.2 (MSH 15-52) [PSR B1509-58] N158A (in LMC) [PSR B0540-69]	G180.0-1.7 (S147) [PSR J0538+2817] G292.2-0.5 [PSR J1119-6127]
Exotic/Possible NS + Supernova Remnant (16+1)	G54.1+0.3 [CXOU J193030.1+185214]	G0.9+0.1 [SAX J1747-2809] G119.5+10.2 (CTA 1) [RX J000702+7302.9] G189.1+3.0 (IC 443) [CXOU J061705.3+222127] G291.0-0.1 (MSH 11-62) [AX J1111-6040]	G27.4+0.0 (Kes 73) [AX J1841-045] (AXP) G29.6+0.1 [AX J1845-0258] (AXP?) G39.7-2.0 [SS 433] (binary) G78.2+2.1 (gamma Cygni) [RX J2020.2+4026] (NS?) G109.1-1.0 (CTB 109) [1E 2259+586] (AXP) G111.7-2.1 (Cas A) [CXO J232327.9+584842] (NS?) G260.4-3.4 (Puppis A) [RX J0822-4300] (NS?) G266.2-1.2 (RX J0852.0-4622) [SAX J0852.0-4615] (NS?) G296.5+10.0 (PKS 1209-51/52) [1E 1207.4-5209] G321.9-0.3 [Cir X-1] (binary) G332.4-0.4 [RCW 103] [1E 161348-5055] (NS?) N49 (in LMC) [SGR 0526-66] (SGR)
X-ray and Radio nebula (9)	G20.0-0.2 G21.5-0.9 G74.9+1.2 G328.4+0.2	G16.7+0.1 G39.2-0.3 G326.3-1.8 (MSH 15-56) G327.1-1.1 G344.7-0.1	
Radio nebula only (8)	G6.1+1.2 G27.8+0.6 G63.7+1.1	G24.7+0.6 G293.8+0.6 G318.9+0.4 G322.5-0.1 G351.2+0.1	

Questions:

- ◆ “Typical” neutron stars have told us that we have a lot to learn about relativistic plasmas and accretion.
- ◆ How does a neutron star cool? What is inside?
- ◆ How strong is the crust of a neutron star?
- ◆ What is the neutron star ocean like?
- ◆ How viscous is the stuff inside?

Young Cooling Neutron Stars

- The luminosity of young cooling neutron stars is a direct probe of the physics of ultradense matter.
- Is there a quark-gluon phase transition at high chemical potential?



Yakovlev et al. '02

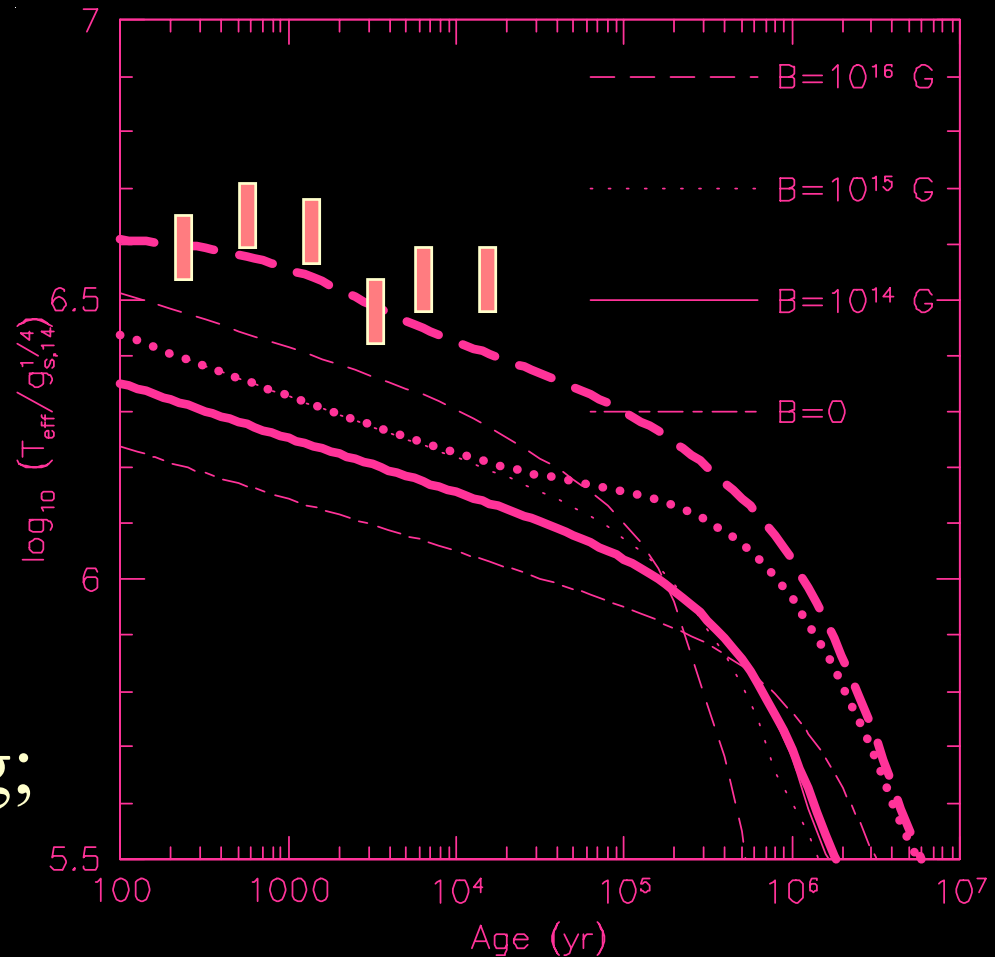
Chakrabarty et al. '01

Anomalous X-ray Pulsars

- ▶ Young isolated neutron stars (often in SNRs):
 - consistent spin down with glitches,
 - periods of several seconds,
 - thermal spectra in X-rays, $L \sim 10^{34}$ erg/s,
 - really faint in optical
 - inferred $B \sim 10^{15}$ G
 - too bright to be standard cooling, too faint for standard accretion
- ▶ Accretion from tiny disk?

Powering the AXP's

- ▶ Magnetic fields play a dominant and dynamic role.
 - Electron conduction,
 - Field decay,
- ▶ Early on neutrinos dominate the cooling; later photons do.



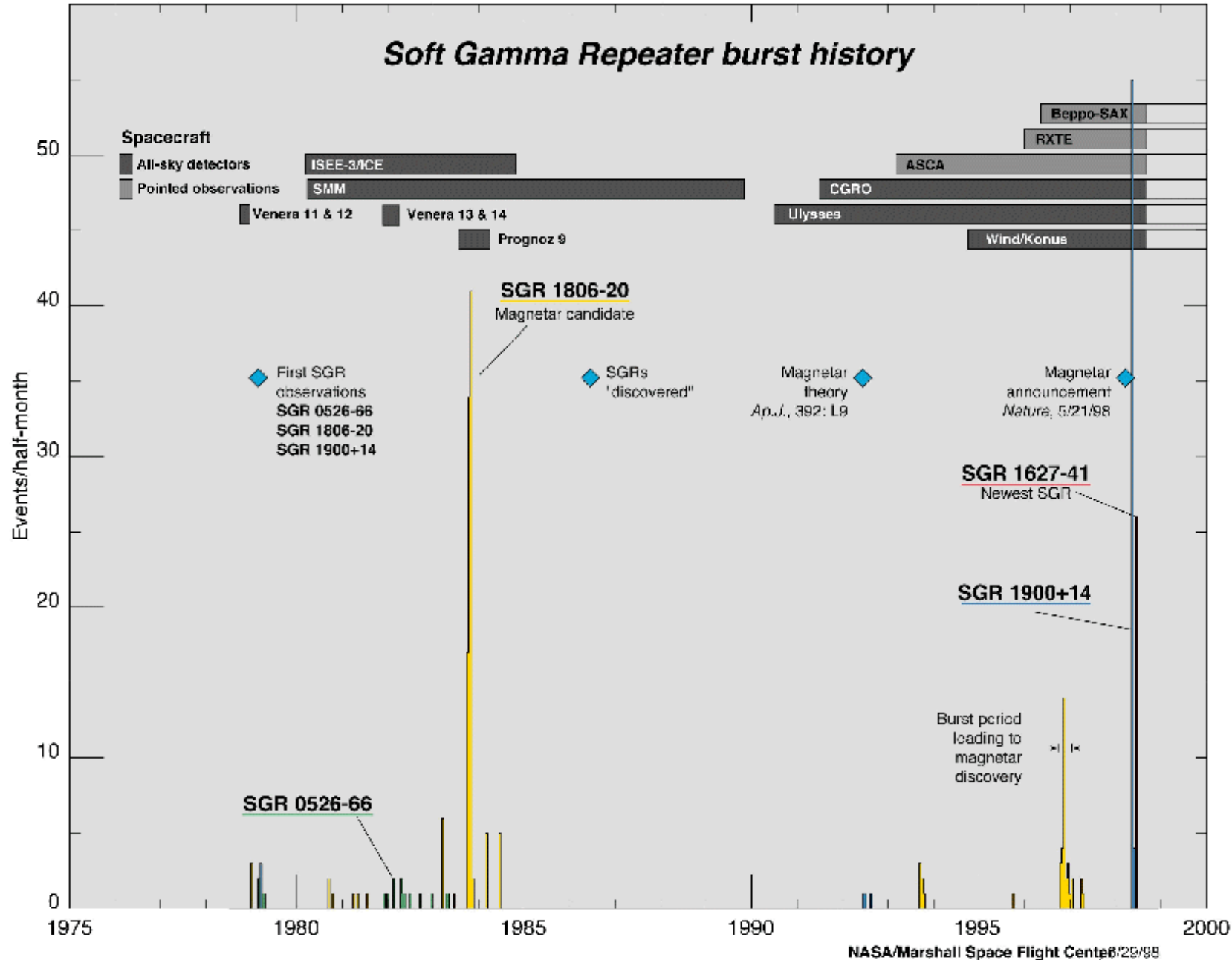
Soft Gamma Repeaters

- Young isolated neutron stars (sometimes in SNRs):
 - consistent spin down,
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 - thermal spectra in X-rays, $L \sim 10^{34}$ erg/s,
 - really faint in optical
 - inferred $B \sim 10^{15}$ G
 - too bright to be standard cooling, too faint for standard accretion

Plus they burst!

- ▶ Bursts last a few tenths of a second and radiate as much energy as the sun does in a year. Soft compared to GRBs.
- ▶ Biggest explosions that don't destroy the source.
- ▶ Magnetic stress builds in the crust until it fractures and the field rearranges itself locally leading to hard X-ray burst.

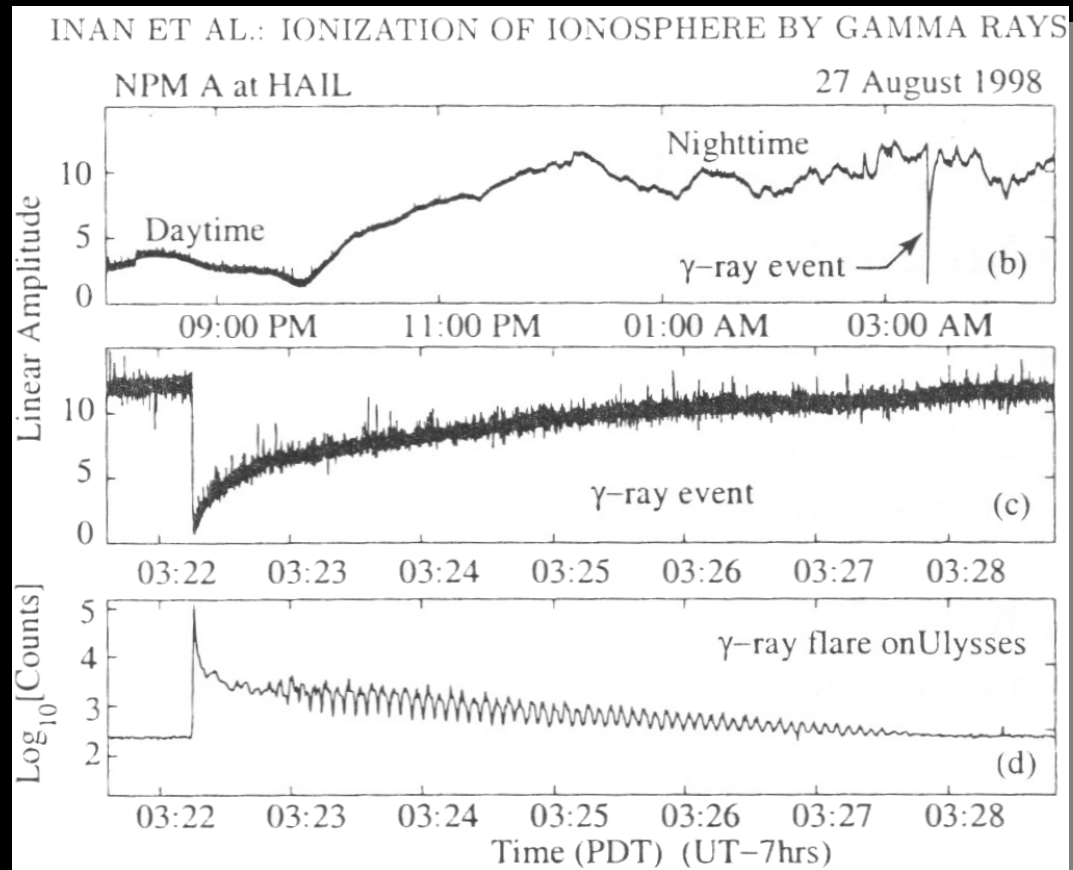
Soft Gamma Repeater burst history



For additional information and illustrations: <http://www.magnetars.com>
 NASA/Marshall Space Flight Center, 9/29/98

Some bursts are really big!

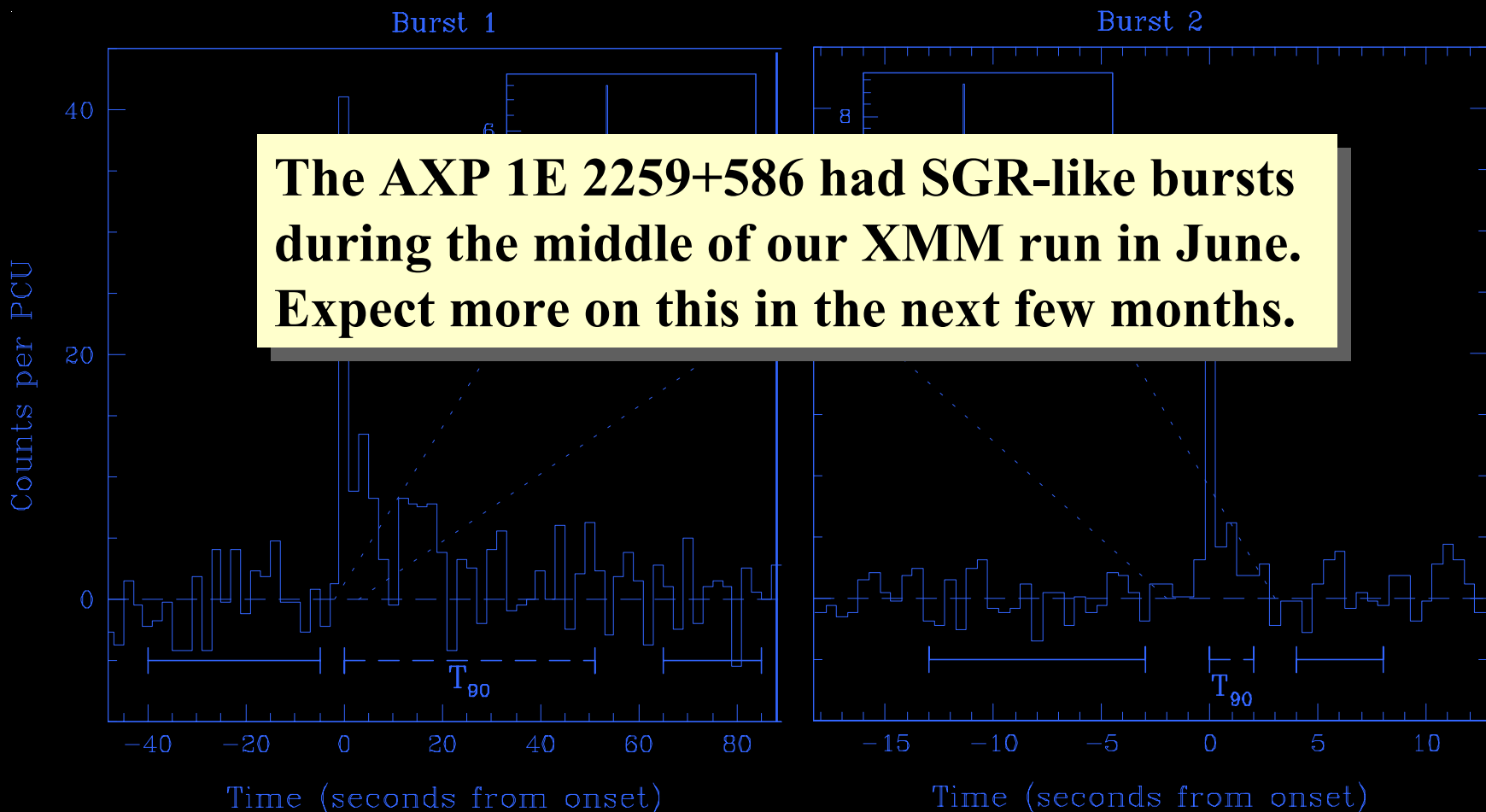
- ▶ March 5, 1979:
SGR 0526-66
- ▶ August 27, 1998:
SGR 1900+14
- ▶ The entire crust is disrupted leading to large-scale reconnection like a solar flare.



The SGR/AXP Connection

- Why do SGRs burst but the AXP's which appear similar don't?
 - Possibly AXP's are younger, a bit hotter, so their crusts are plastic.
 - We haven't been lucky enough to see bursts from AXP's.
 - AXP's may have different and rarer bursts.

But AXPs do burst...



The AXP 1E 2259+586 had SGR-like bursts during the middle of our XMM run in June. Expect more on this in the next few months.

1E1048.1-5937

Gavriil, Kaspi, Woods '02

Young at Heart Neutron Stars

► Sources of energy:

- gravitational
- thermonuclear
- pycnonuclear
- spin

► Tapping the energy:

- accretion
- steady v. bursts
- neutrinos v. photons
- gravitational waves v. magnetic dipole radiation

A Low Mass X-Ray Binary: 4U 1820-30

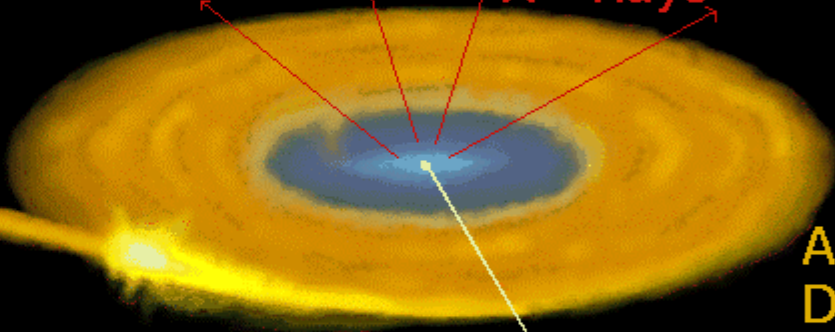


130,000 km

White Dwarf



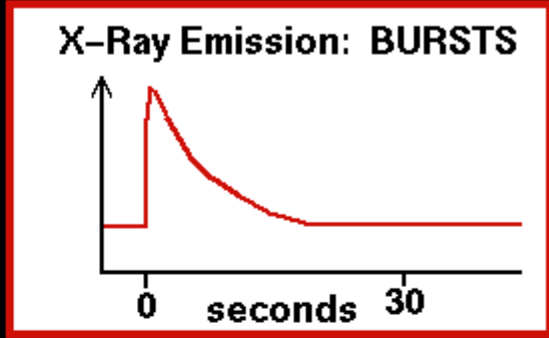
1,200 km/sec



X - Rays

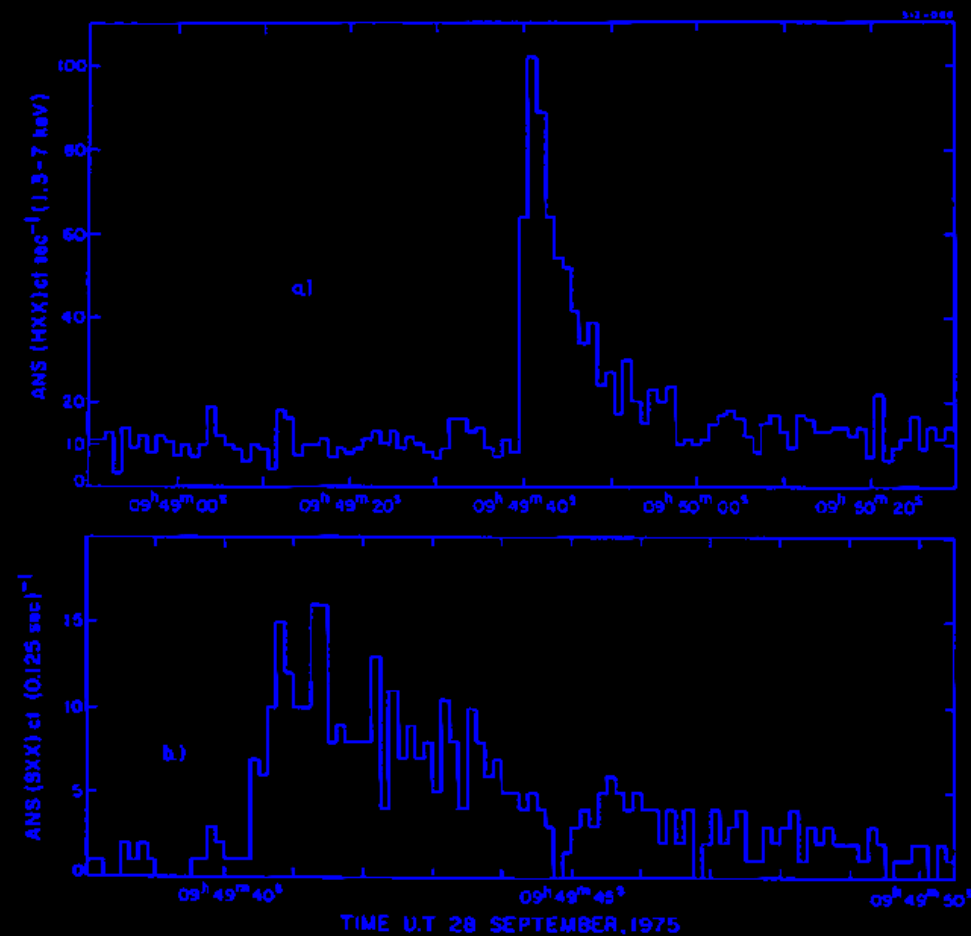
Accretion Disk

Neutron Star

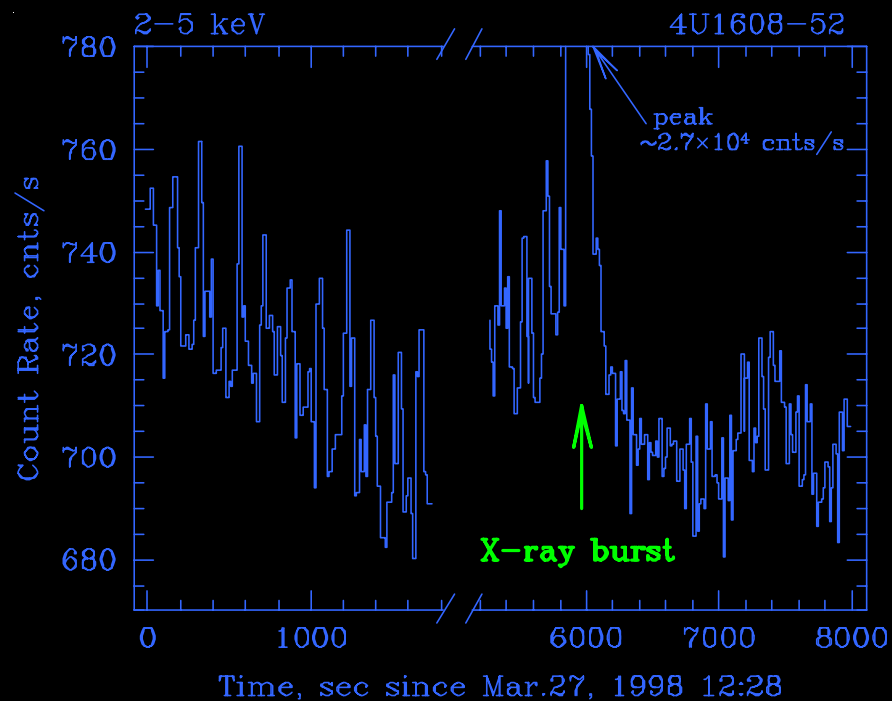


SUN

Plus they burst! - X-ray novae



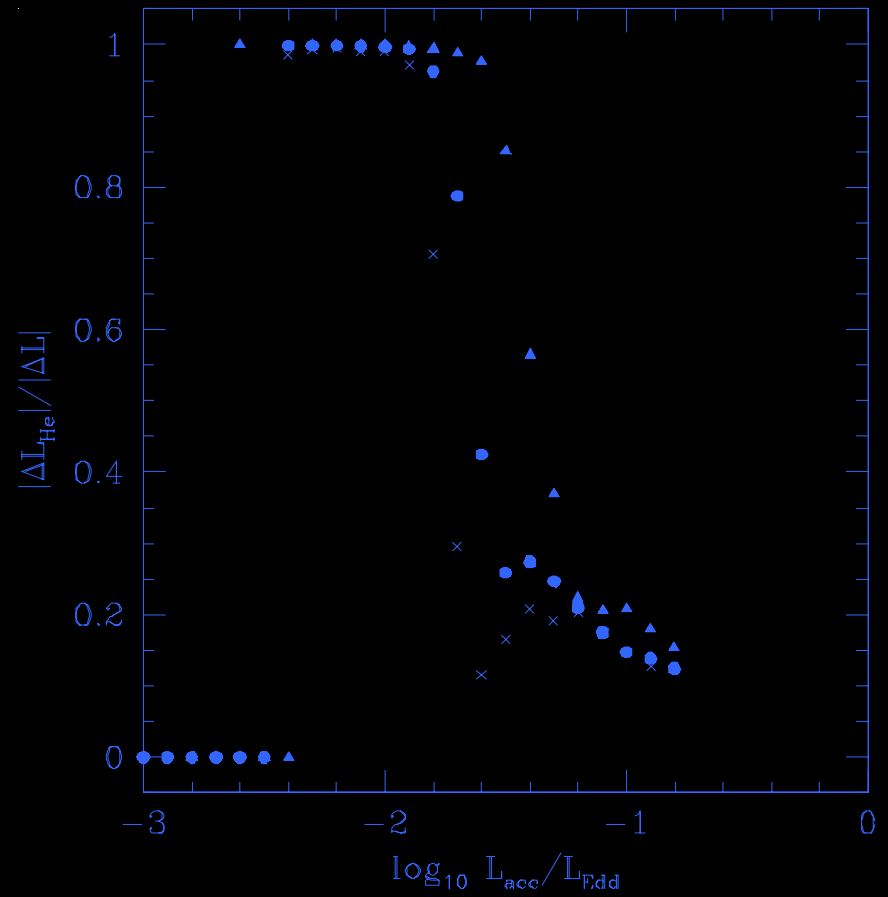
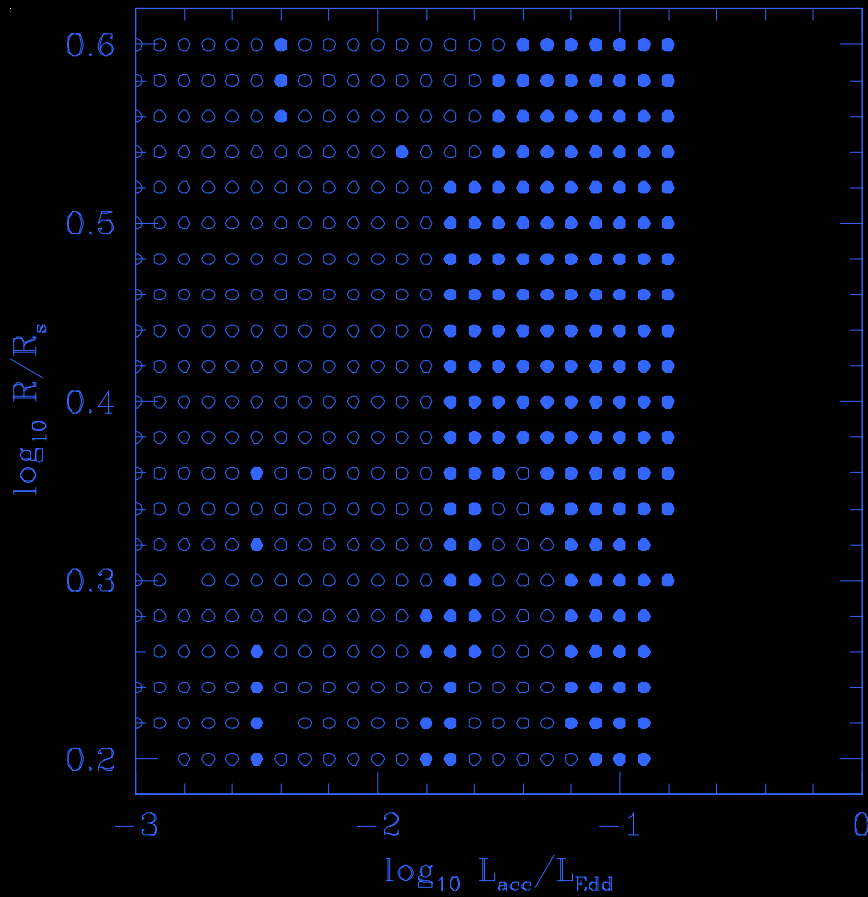
Grindlay et al. '76 (ANS)



Revnivtsev '01 (RXTE)

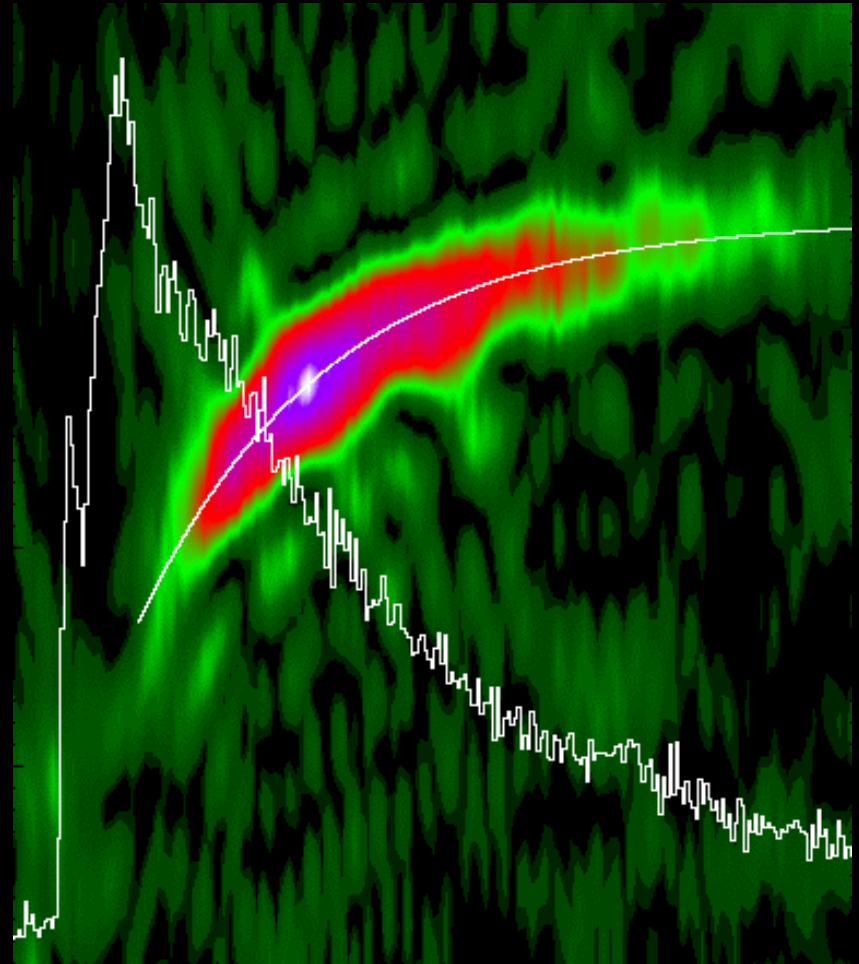
JSH, Narayan '02

Reexamining Type-I Bursts



Burst Oscillations

- ▶ During the cooling portion of the burst, the observed frequency increases by about one Hertz.
- ▶ If the oscillation corresponded to the spin of the star, its frequency should be constant.



Strohmayer '97

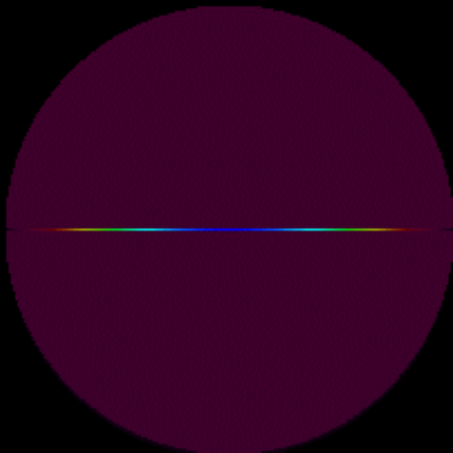
Neutron-Star Surface Waves

- ▶ As the star rotates, the flux will vary at the angular frequency $|m\Omega - \omega|$.
 - Waves which travel with the rotation of the star will vary faster.
 - Waves which travel against the rotation of the star will vary more slowly.
- ▶ The frequency changes by 1 part in 300, so $\Omega/\omega \approx 300$.

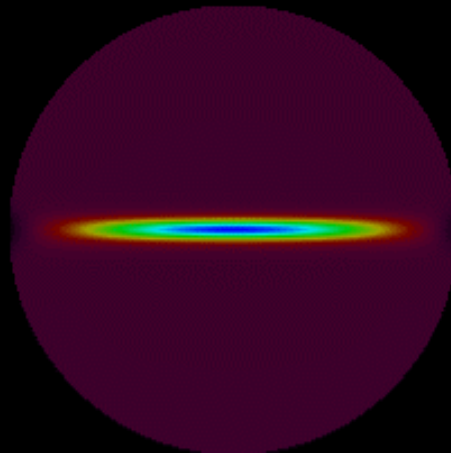
Neutron-Star Stripes

- ◆ Frequencies decrease with the number of radial and latitudinal nodes!
- ◆ The surface waves with the highest frequencies are:

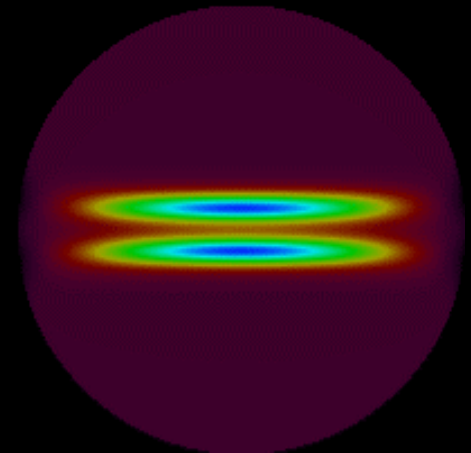
Earth



Gravity wave



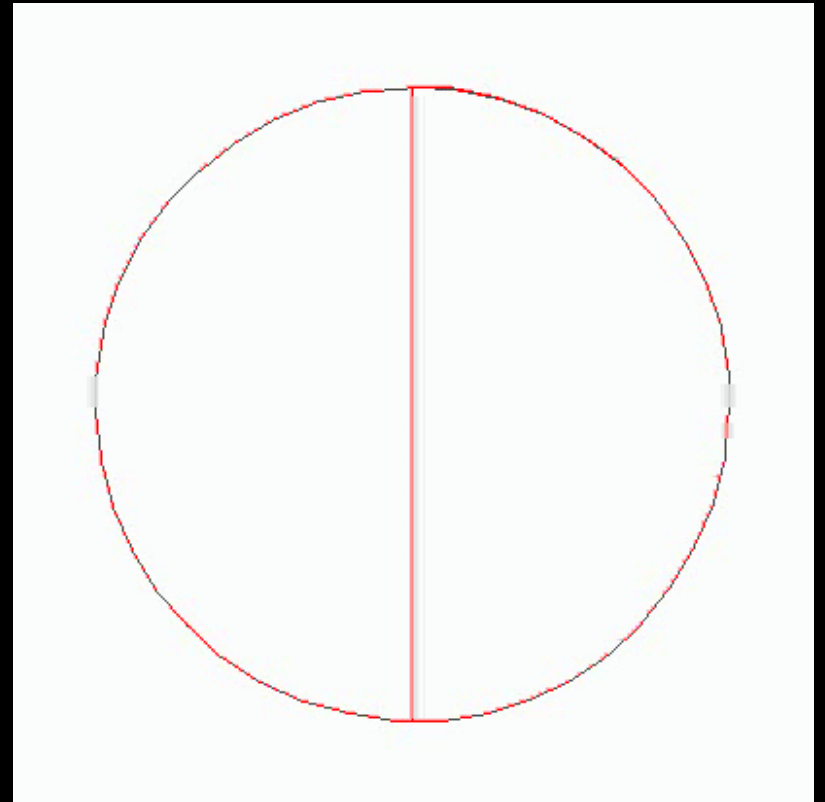
Kelvin wave



Rossby Wave

More on Rossby Waves

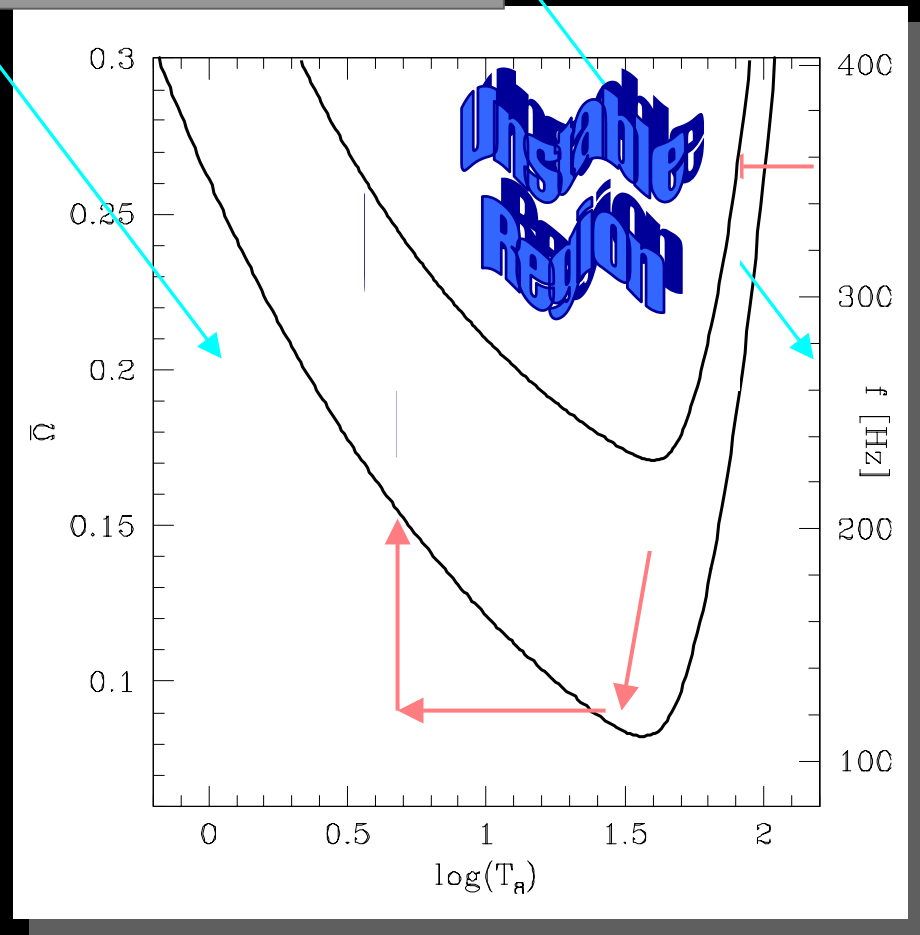
- ◆ The presence of an r-mode reduces the angular momentum of the star.
- ◆ The lump of material rotates with the star; GW carry angular momentum away, amplifying the r-mode.



What if the fluid is viscous?

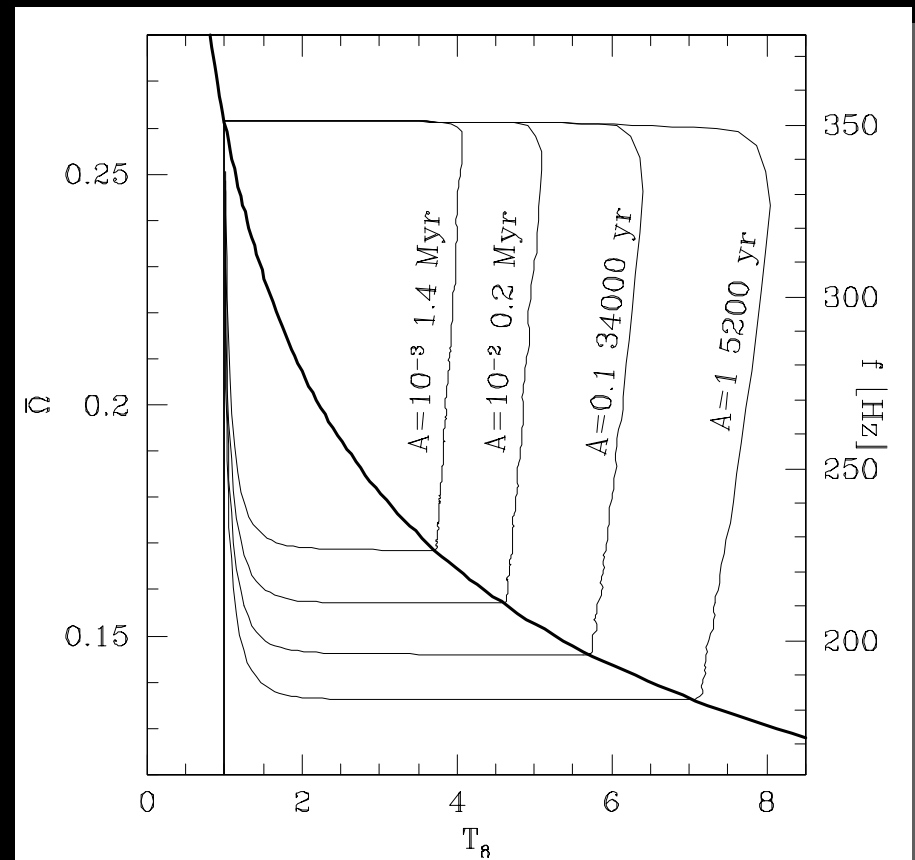
Shear viscosity decreases Bulk viscosity increases with T

- Viscosity damps fluid motions. Its effects are strongest for small wavelengths.
- Even a large scale mode has a large gradient in a boundary layer.
- Intermode coupling



Shivering Neutron Stars

- As the peak amplitude decreases, the duration of spin-down goes up, so an object is more likely to be spinning down.
- If the spin-down lasts more than 1,000 yr, T_{surf} will reflect it.



Conclusions

- ▶ Exotic neutron stars may not be so rare.
 - Highly magnetized neutron stars may be as common as standard radio pulsars, but they don't radio out their locations so they are harder to find.
- ▶ Neutron stars may not be so exotic.
 - We can constrain the properties of neutron star material with today's data and learn more in the near future.