The Secret Life of Neutron Stars

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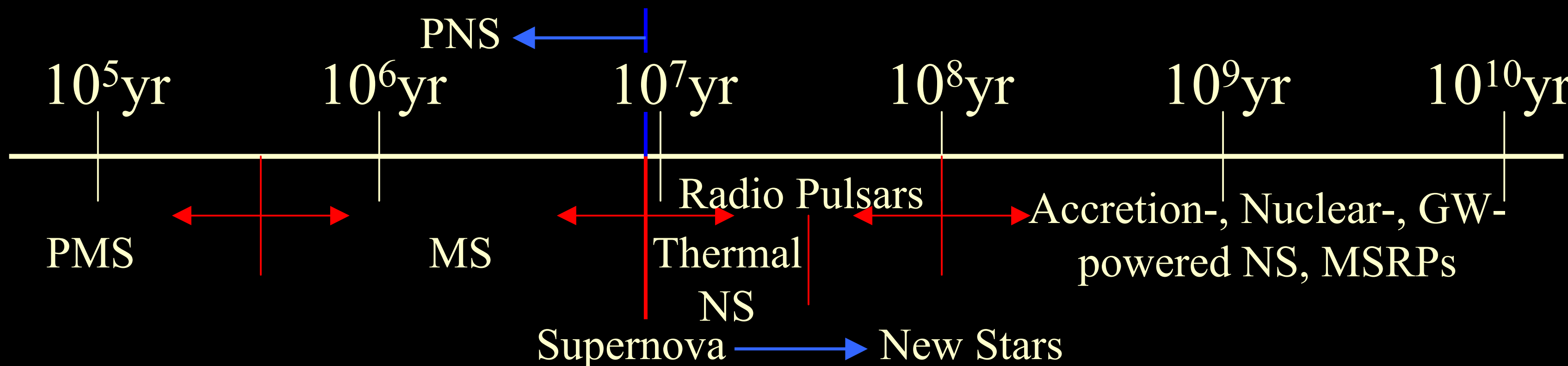
Harvard-Smithsonian CfA

The Life of a 10 $M_\odot$ Star

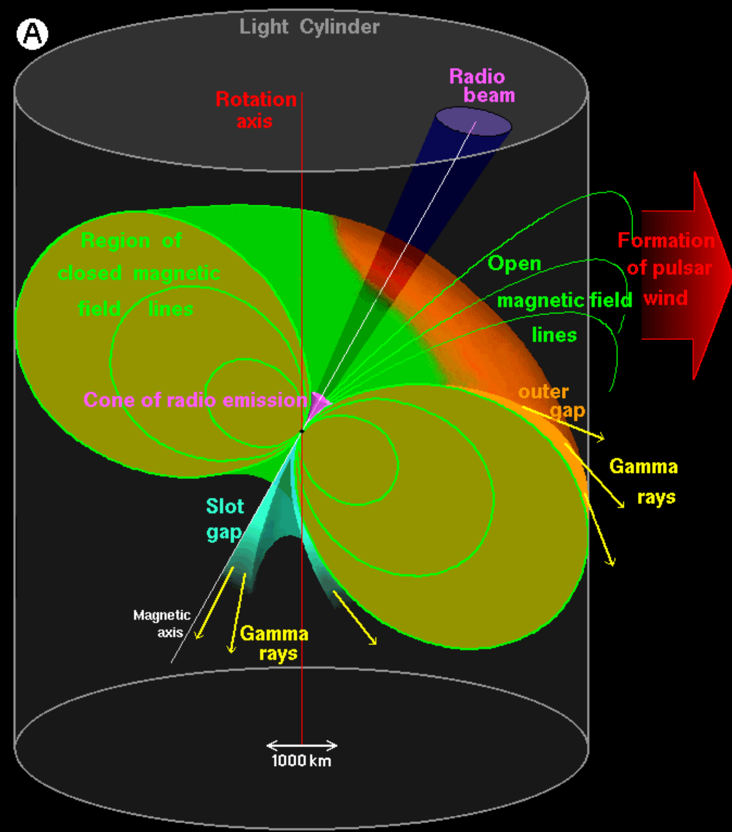


- 12:52am - reaches MS
- 8:45am - leaves MS
- 5:30pm - thermal emission too faint
- 3:40pm on Jan 4 - dead radio pulsar
- June 30 - companion overfills Roche lomb; LMXB, Type-I bursts, gravitational radiation
- Nov 10 - MSRP forms as accretion ceases

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



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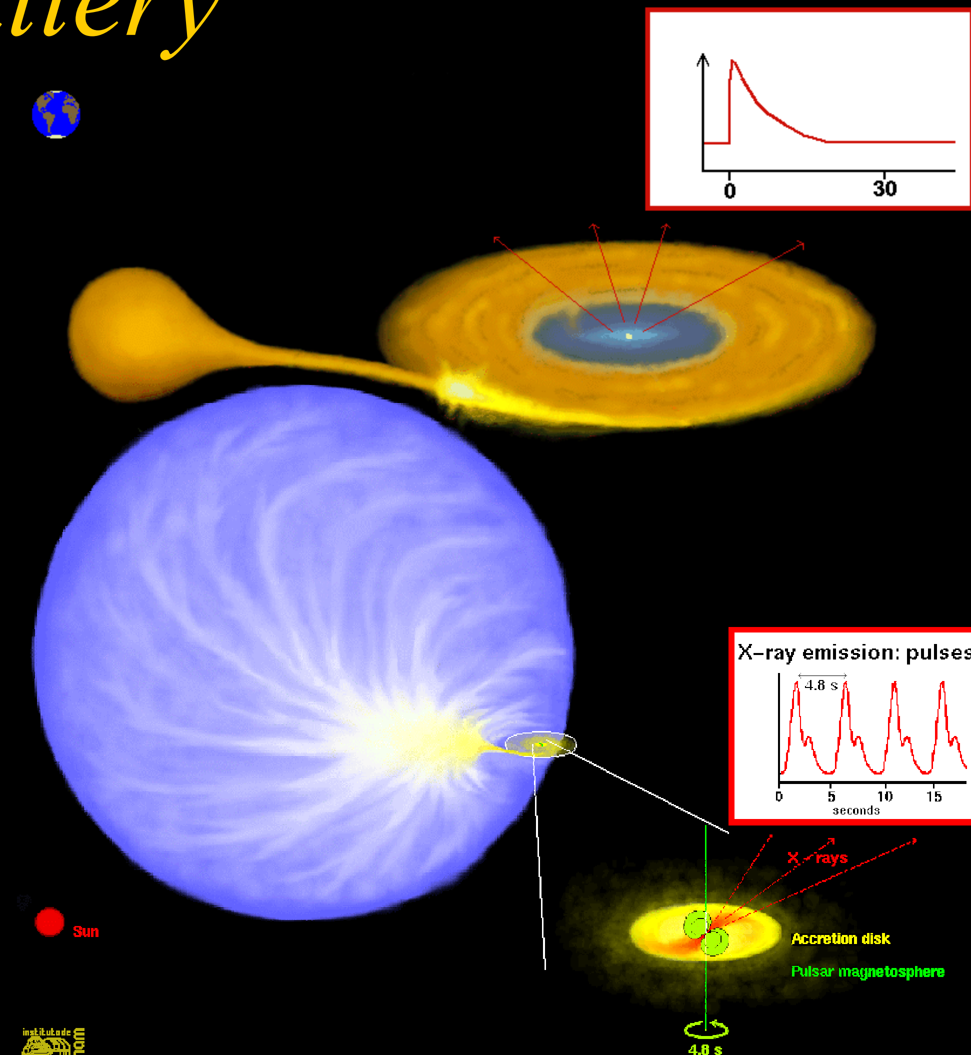

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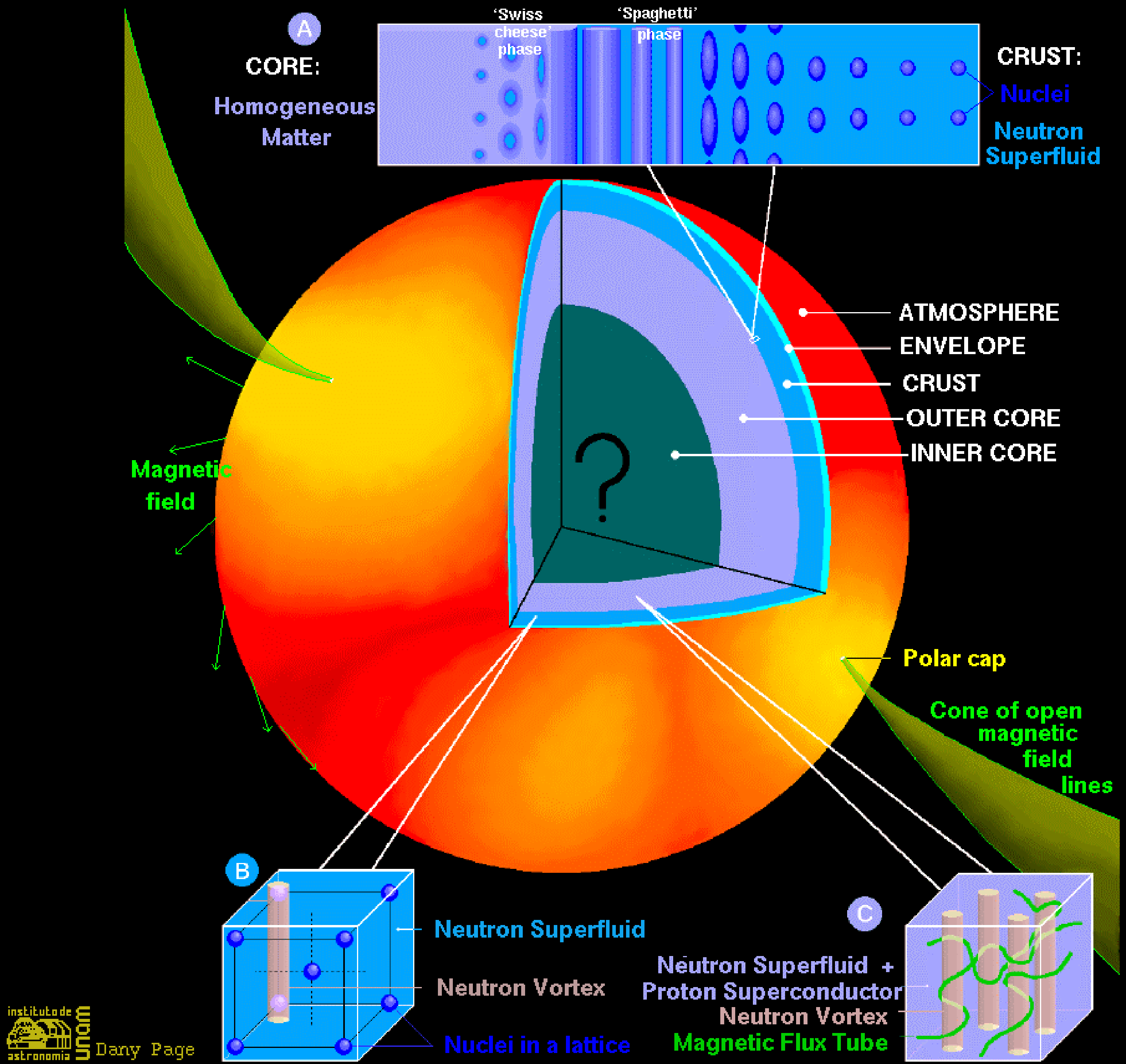
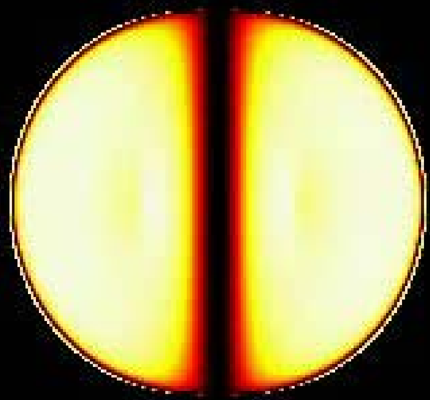
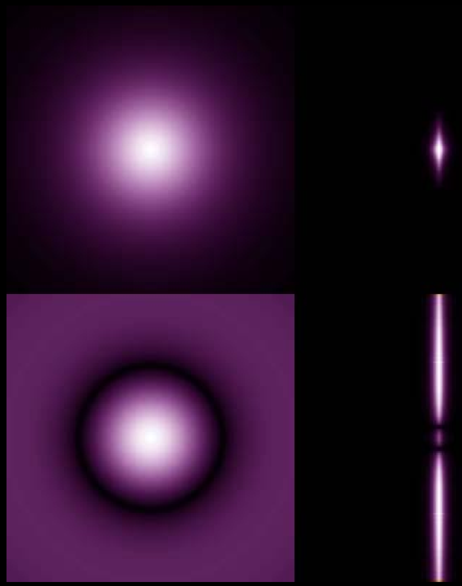
A NEUTRON STAR: SURFACE and INTERIOR

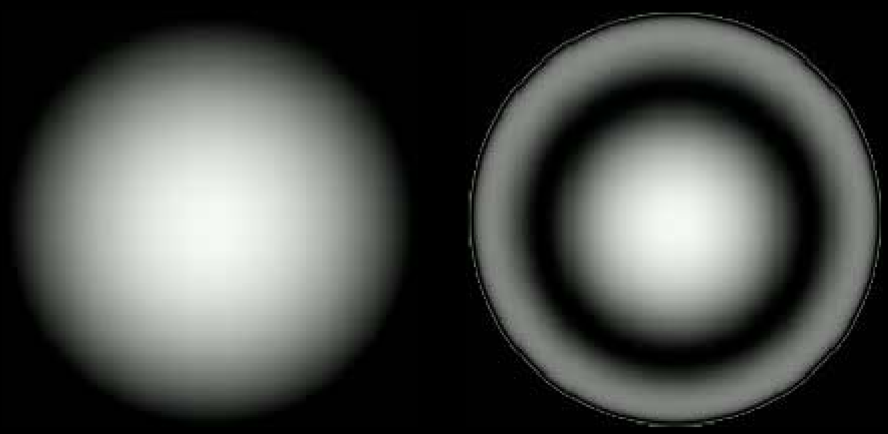




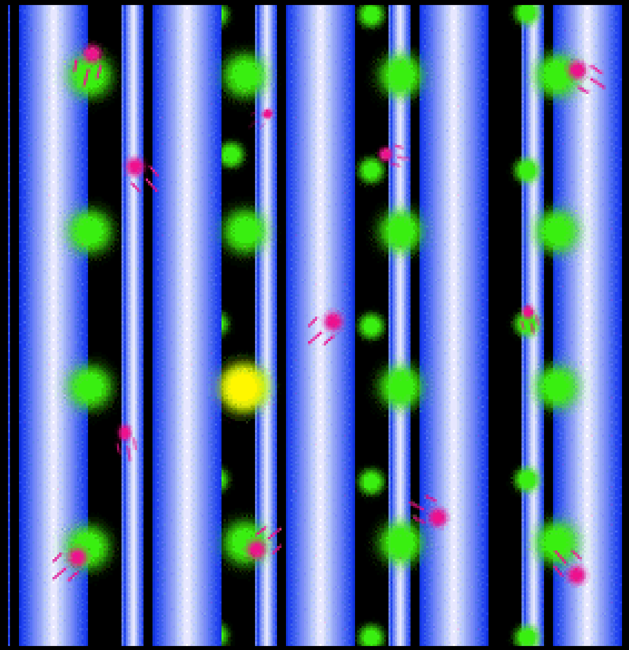
MAGNETOSPHERE: Magnetic Lensing



ATMOSPHERE: Magnetic Atoms



MAGNETOSPHERE: Gravitational Lensing



ENVELOPE: Anisotropic Heat Conduction

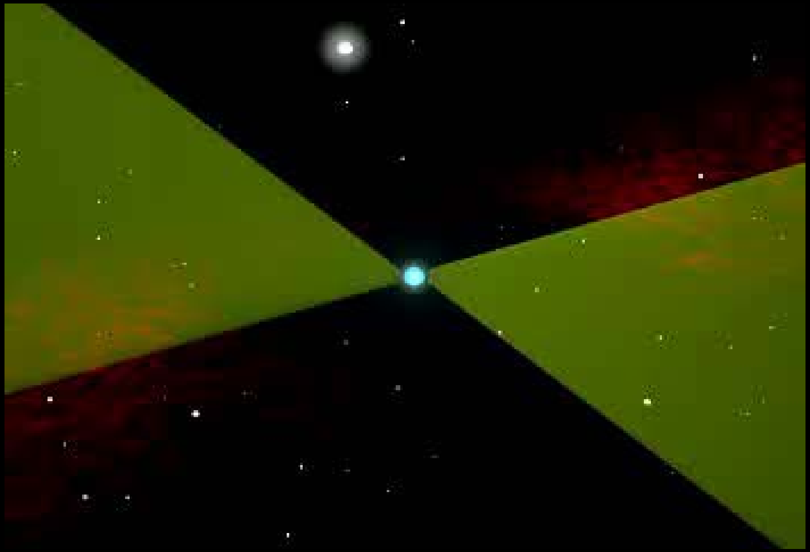
JSH, Hernquist; Shaviv, JSH, Lithwick '99

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 $10^{2\text{-}3}$ yr.
  - magnetic field: typical radio pulsars have $\sim 10^{11\text{-}13}$ 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 15−5*2*) [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 11−6*2*) [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 15−5*6*) 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	

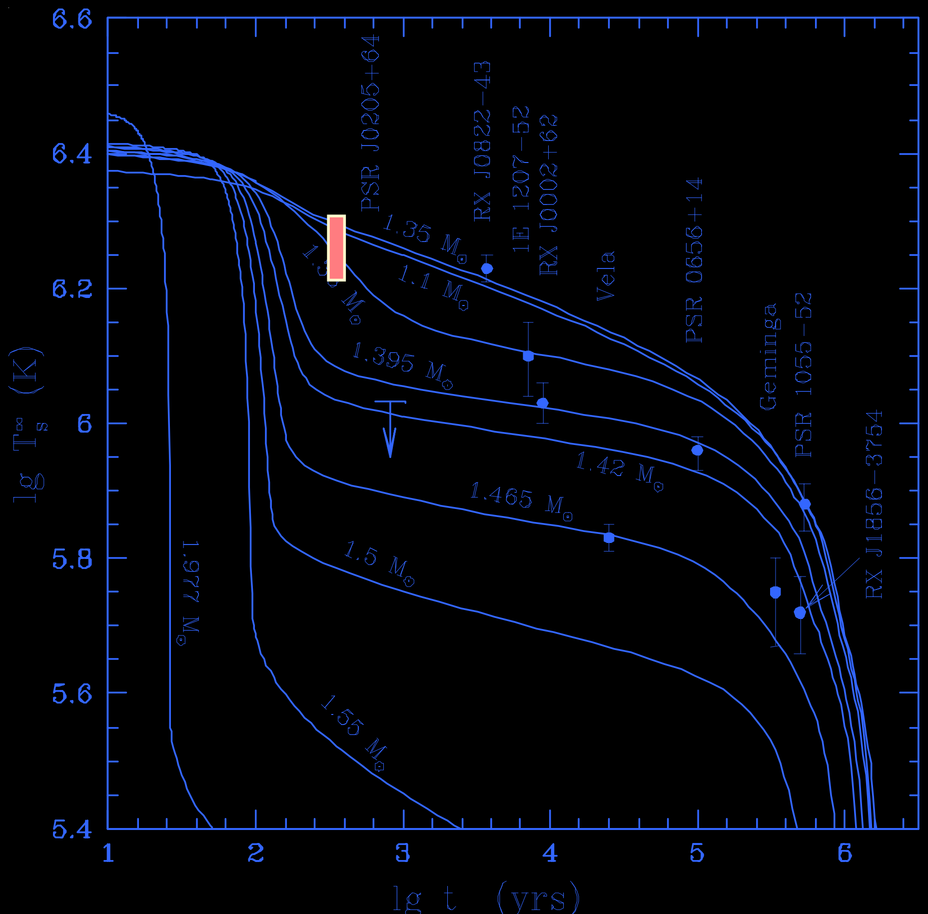
Kaspi & Helfand '02

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

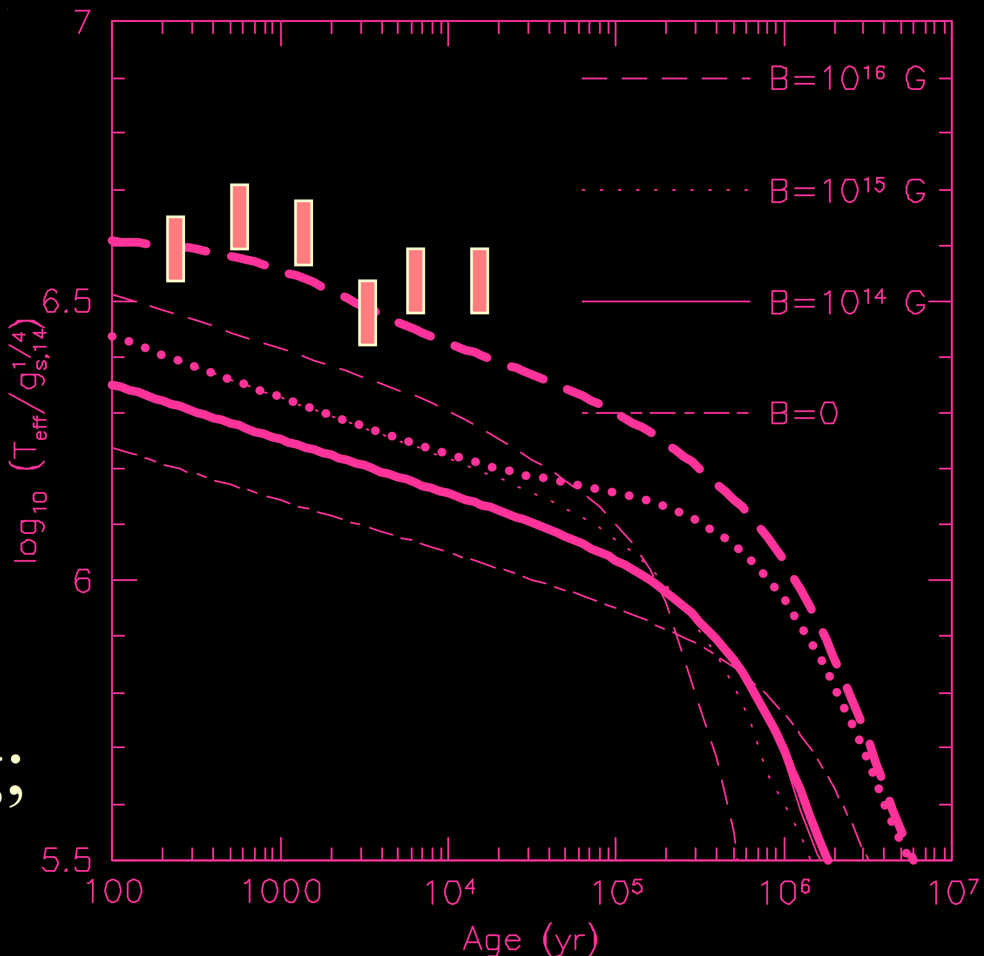
Chakrabarty et al. '01

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 AXPs

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



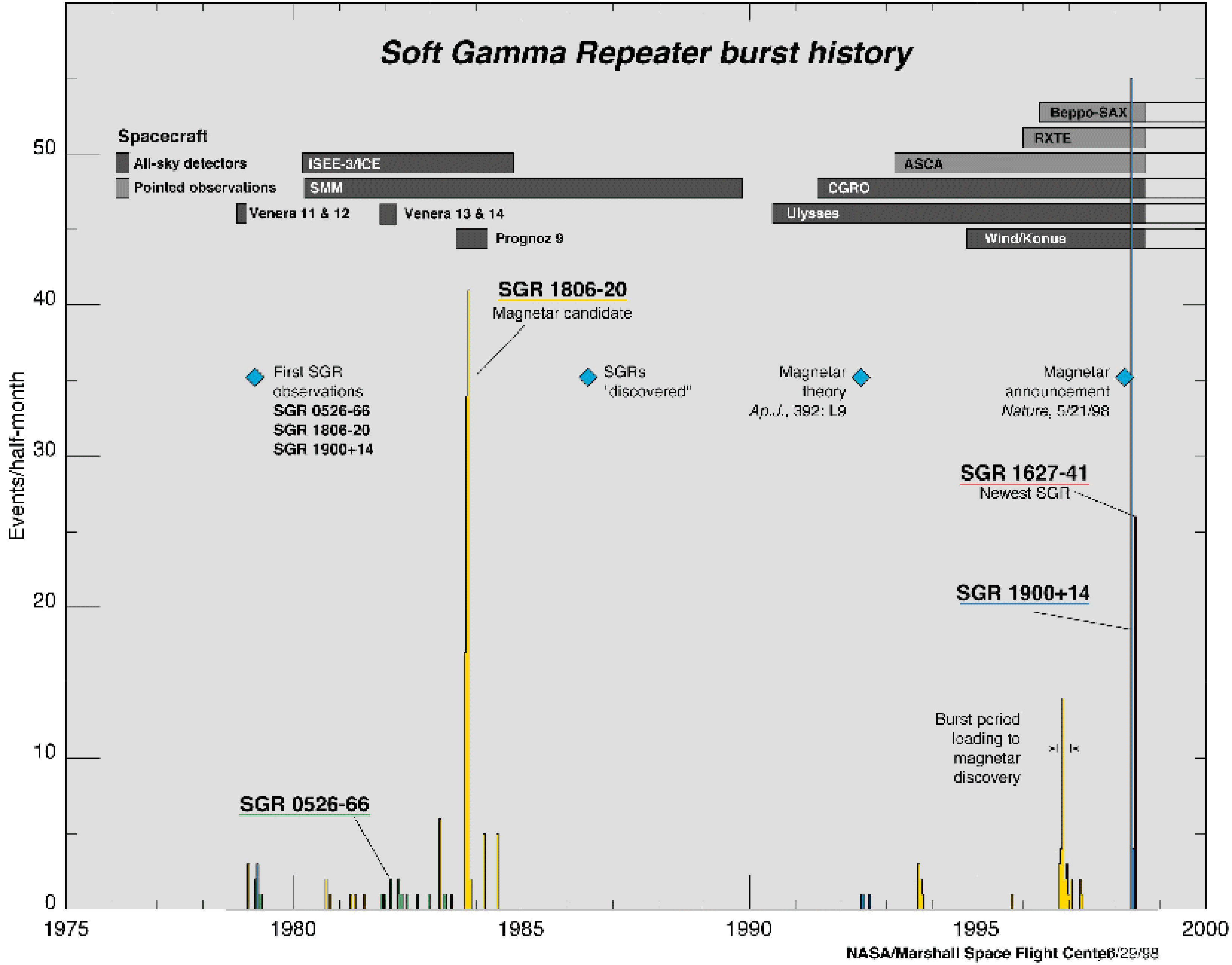
JSH, Kulkarni '98; Perna, JSH … '01

Soft Gamma Repeaters

- Young isolated neutron stars (sometimes in SNRs):
  - consistent spin down,
  - 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

Plus they burst!

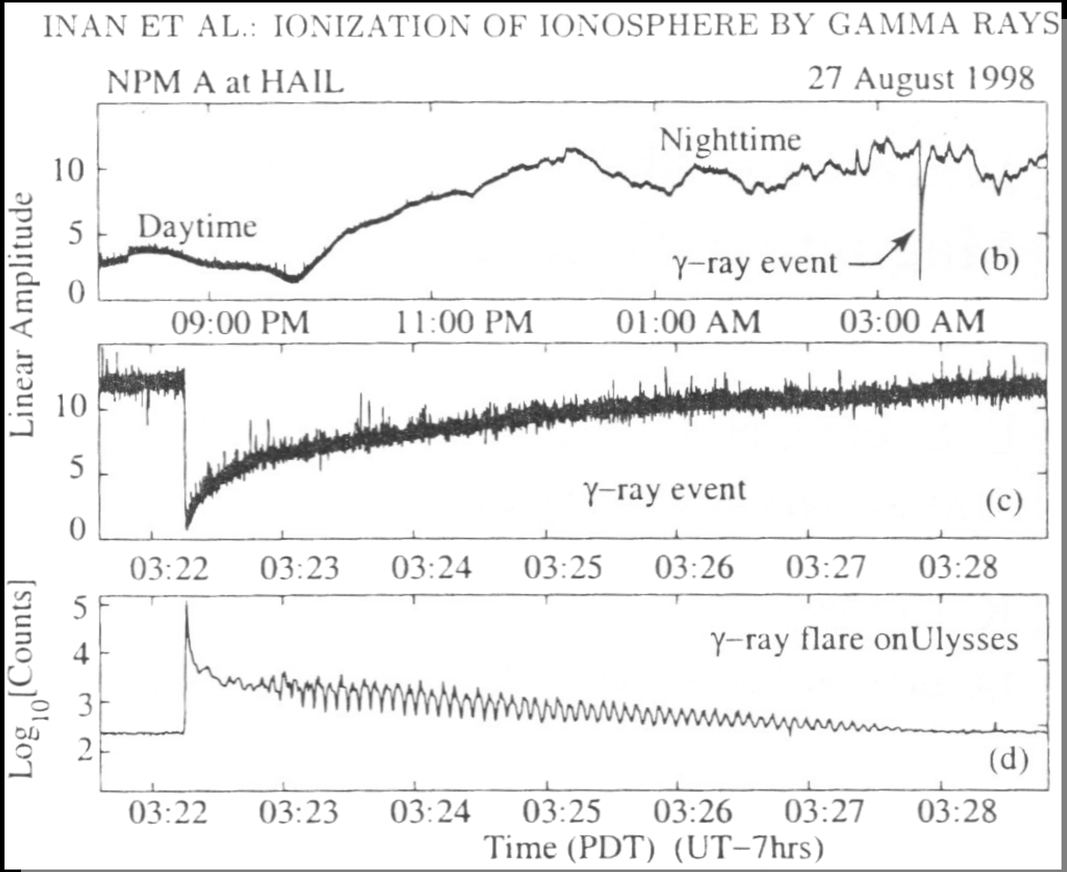
- Bursts last a few tenths of a second and radiate as much energy as the sun does in a year. Soft compared to GRBs.
- Biggest explosions that don't destroy the source.
- Magnetic stress builds in the crust until it fractures and the field rearranges itself locally leading to hard X-ray burst.



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

Some bursts are really big!

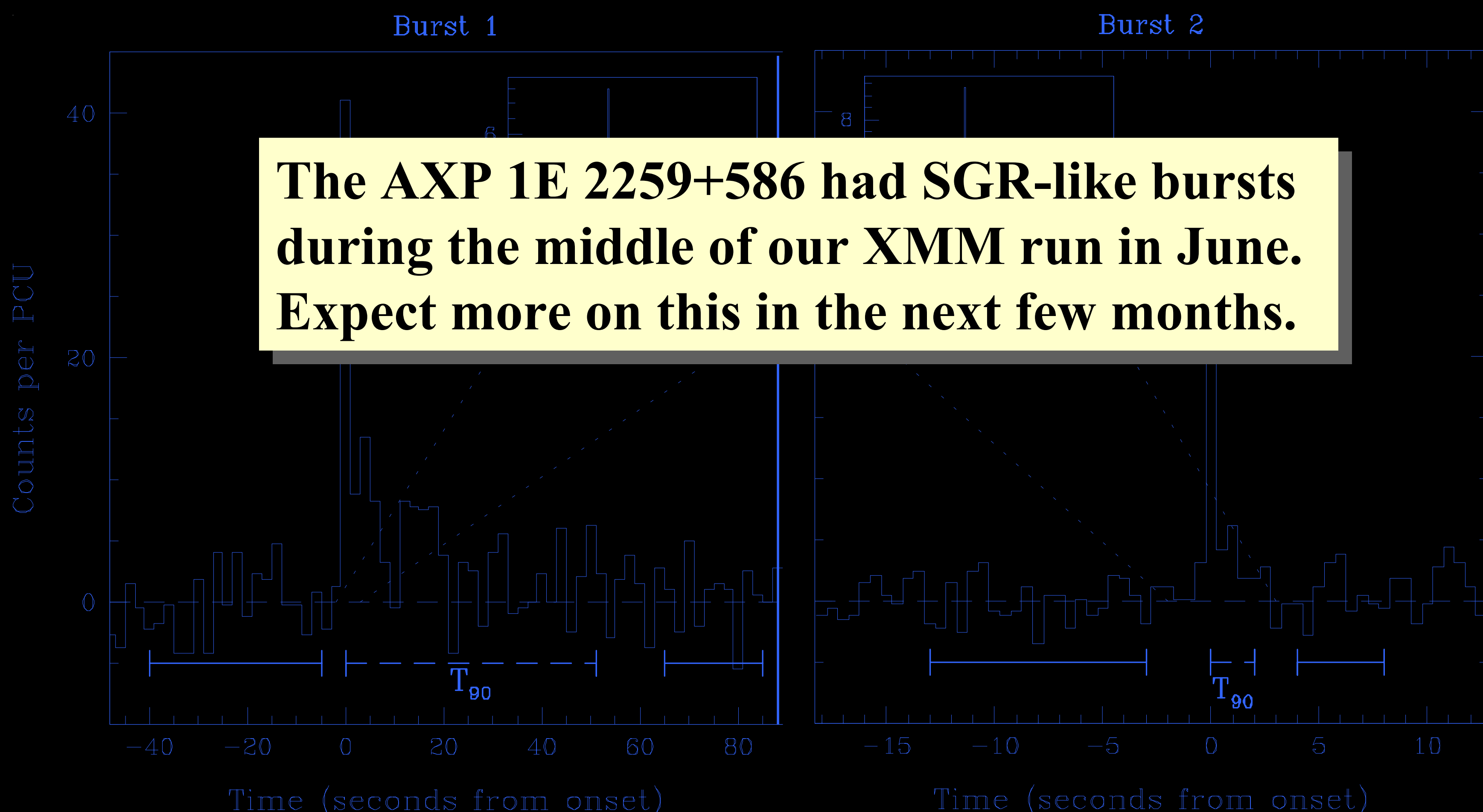
- March 5, 1979: SGR 0526-66
- August 27, 1998: SGR 1900+14
- The entire crust is disrupted leading to large-scale reconnection like a solar flare.



The SGR/AXP Connection

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

But AXPs do burst...



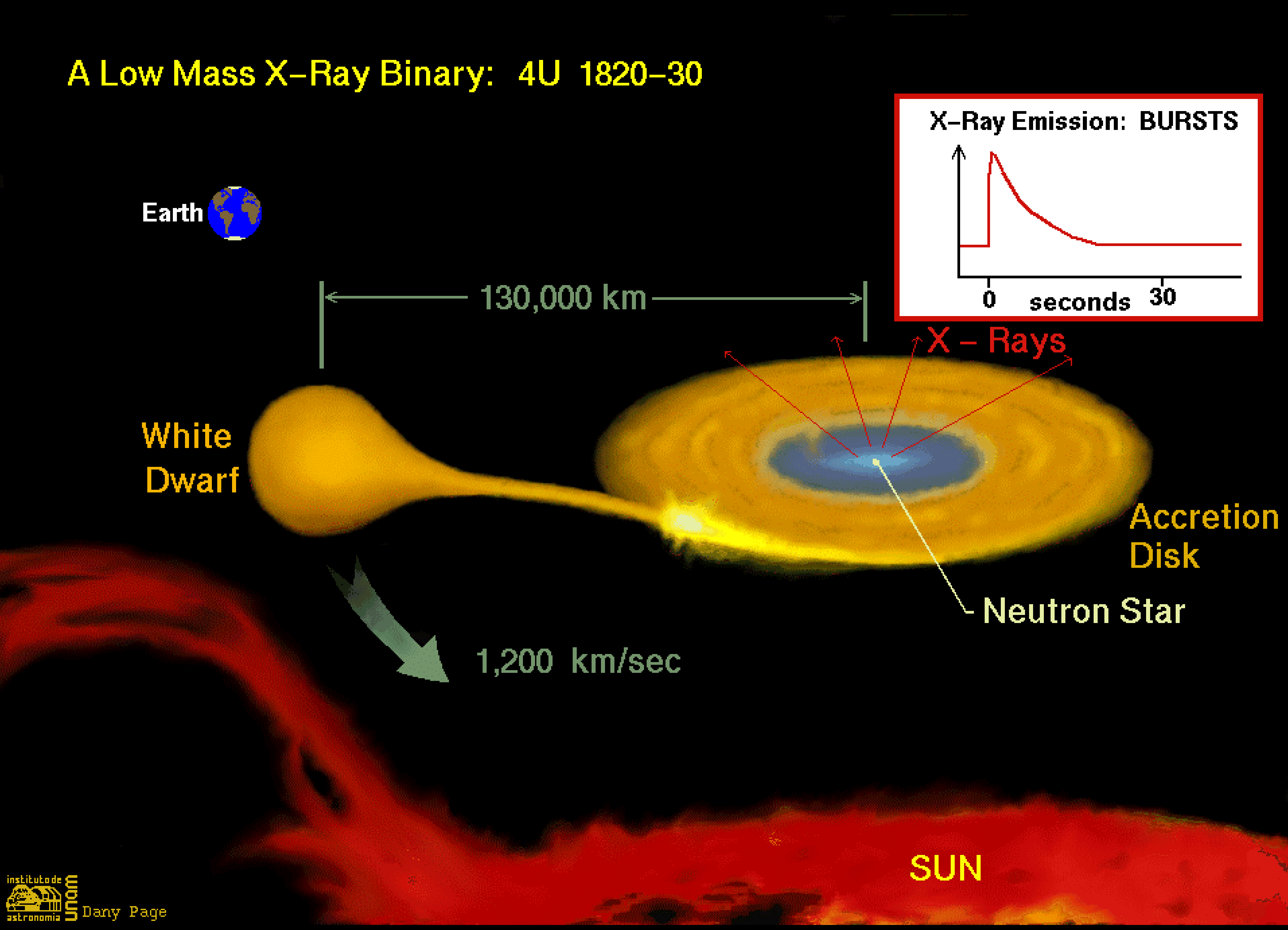
The AXP 1E 2259+586 had SGR-like bursts during the middle of our XMM run in June. Expect more on this in the next few months.

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
X-Ray Emission: BURSTS
0
seconds
30
Earth
130,000 km
X - Rays
White
Dwarf
Accretion
Disk
Neutron Star
1,200 km/sec
SUN
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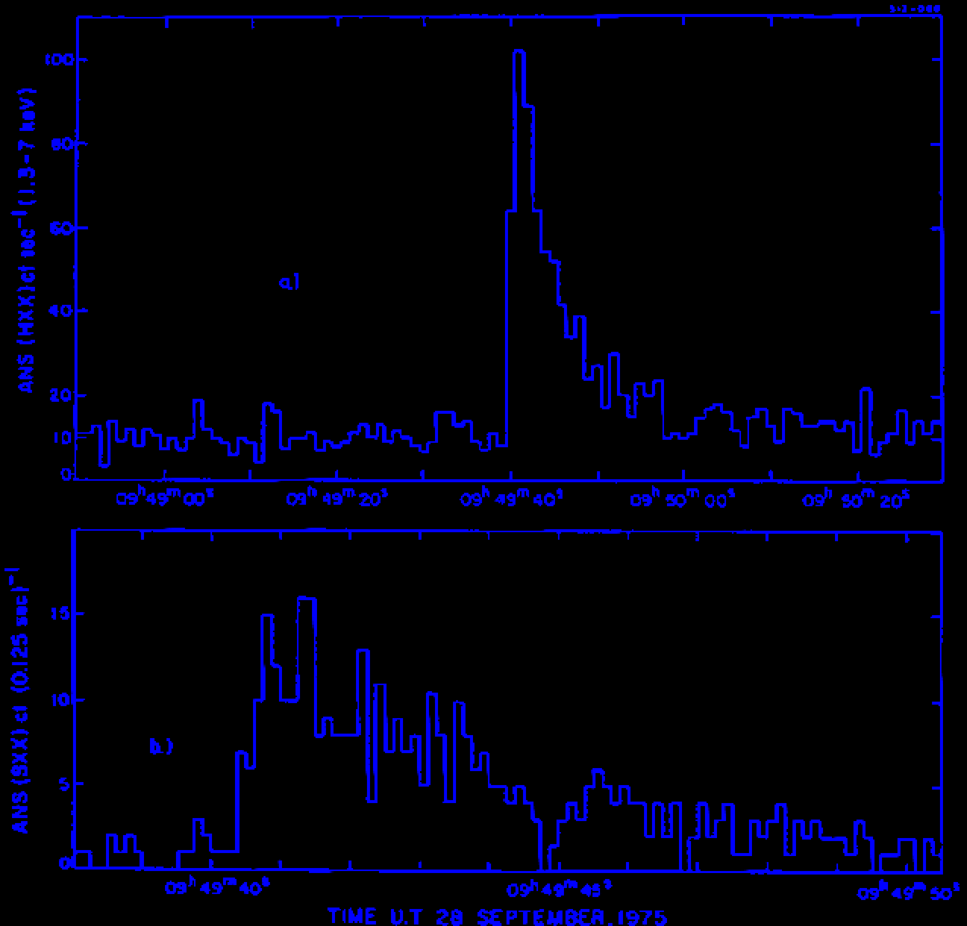
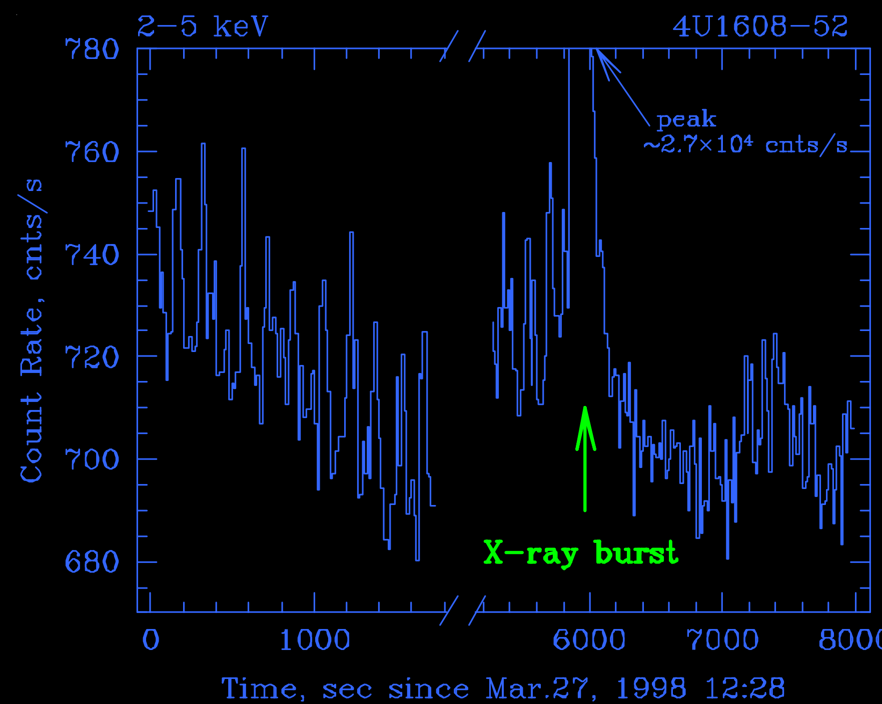
Plus they burst! - X-ray novae



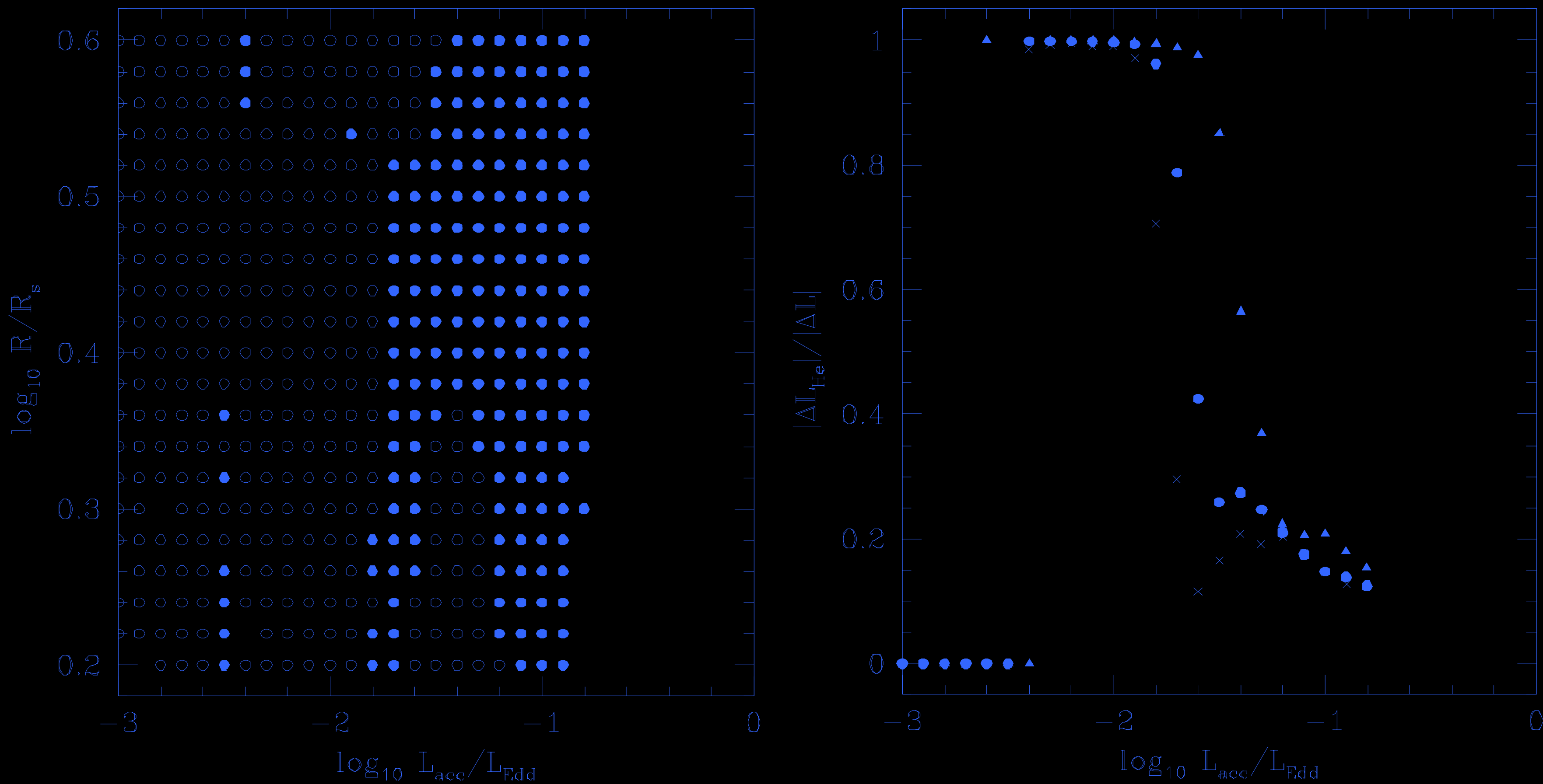
Grindlay et al. ‘76 (ANS)



Revnivtsev ‘01 (RXTE)

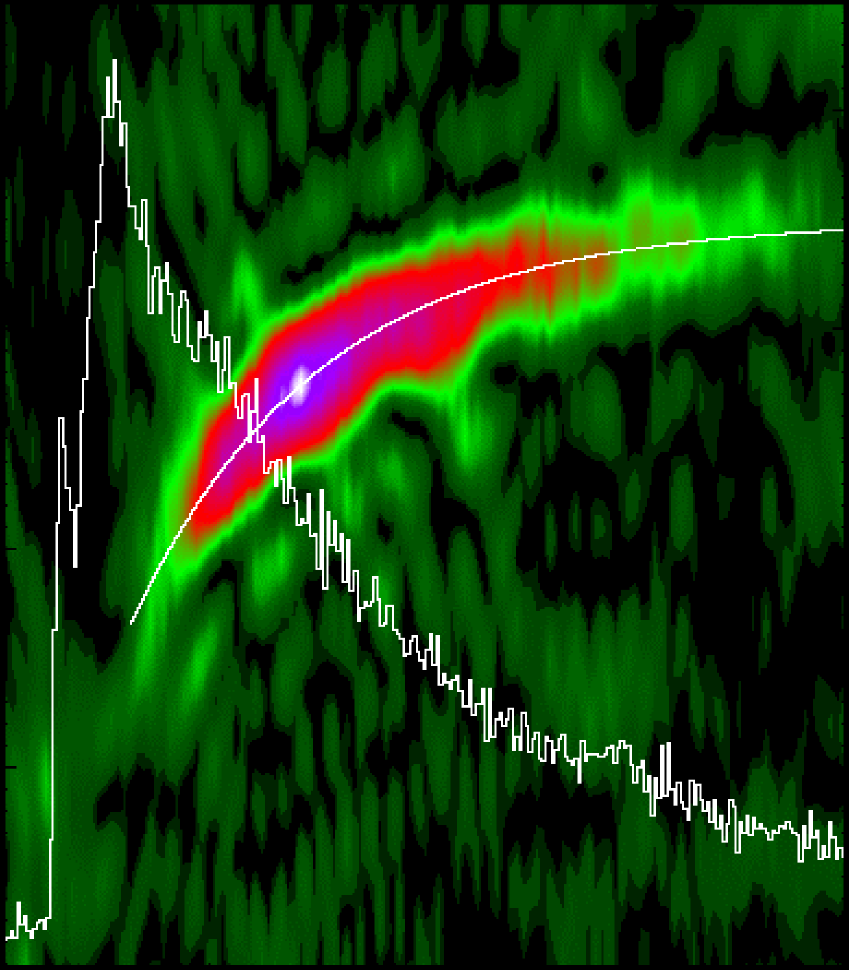
JSH, Narayan ‘02

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

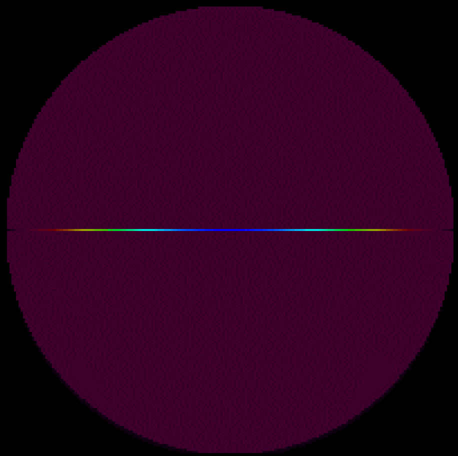
Neutron-Star Surface Waves

- 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 $\Omega/\omega \approx 300$.

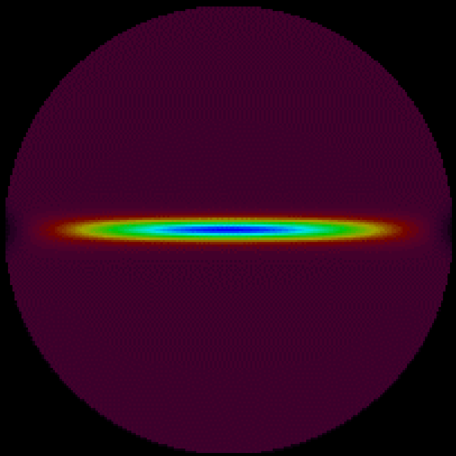
Neutron-Star Stripes

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

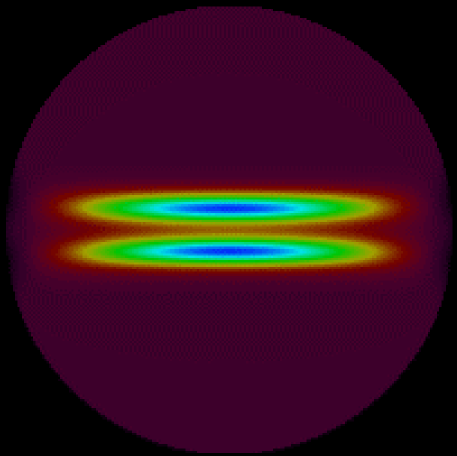
Earth



Gravity wave



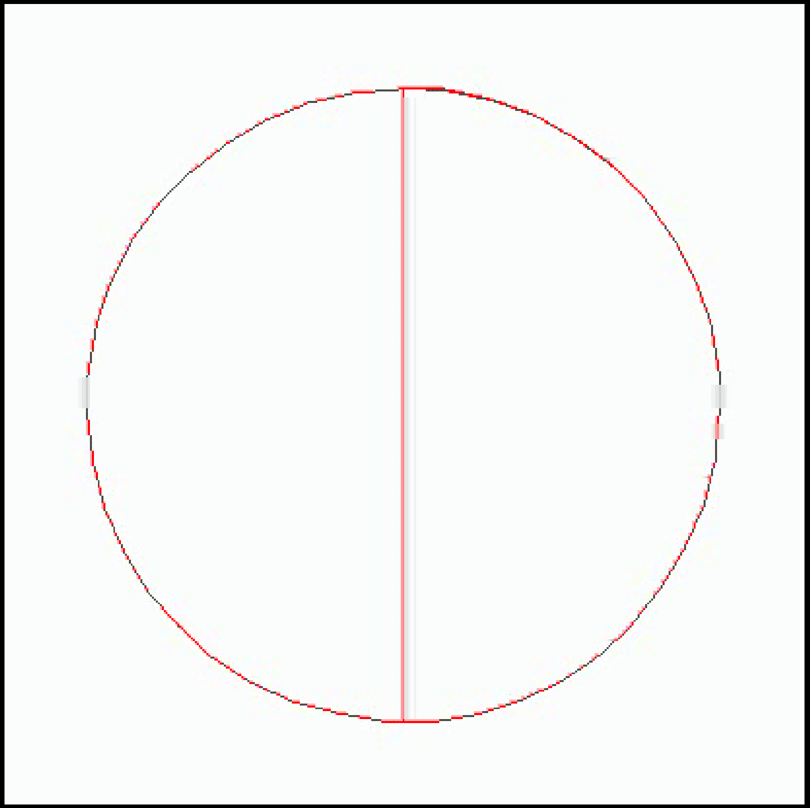
Kelvin wave



Rossby Wave

More on Rossby Waves

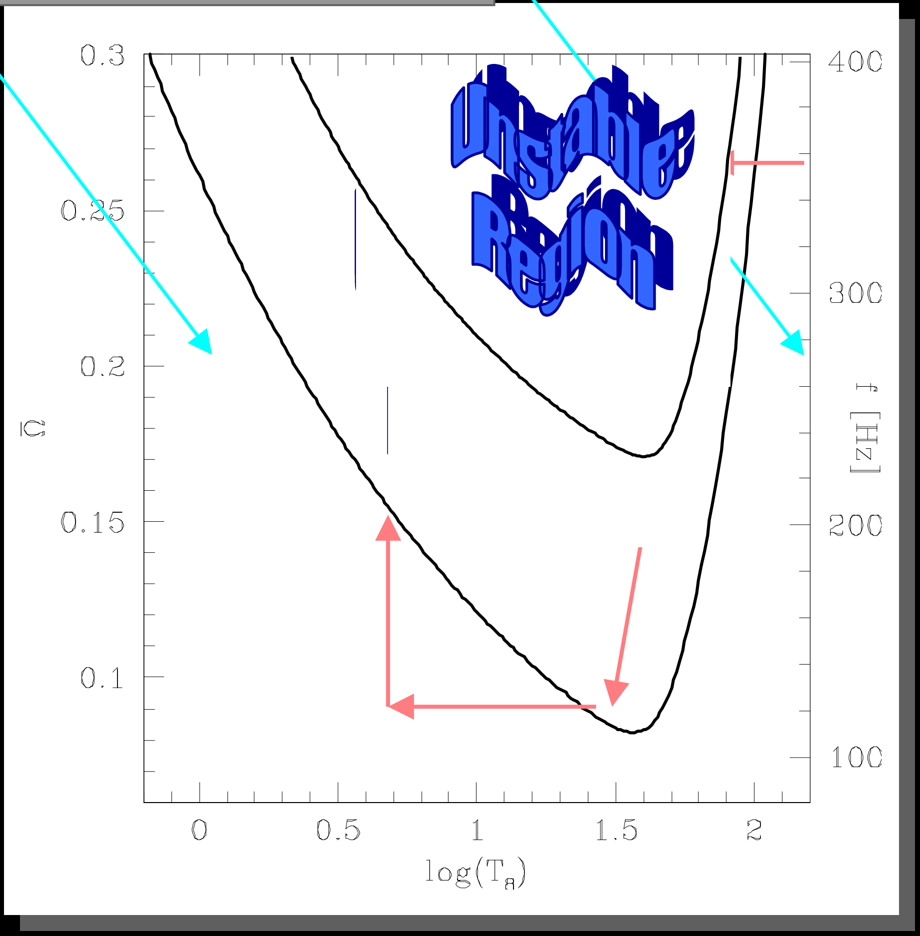
- The presence of an r-mode reduces the angular momentum of the star.
- The lump of material rotates with the star; GW carry angular momentum away, amplifying the r-mode.



What if the fluid is viscous?

Shear viscosity decreas Bulk viscosity increases with T

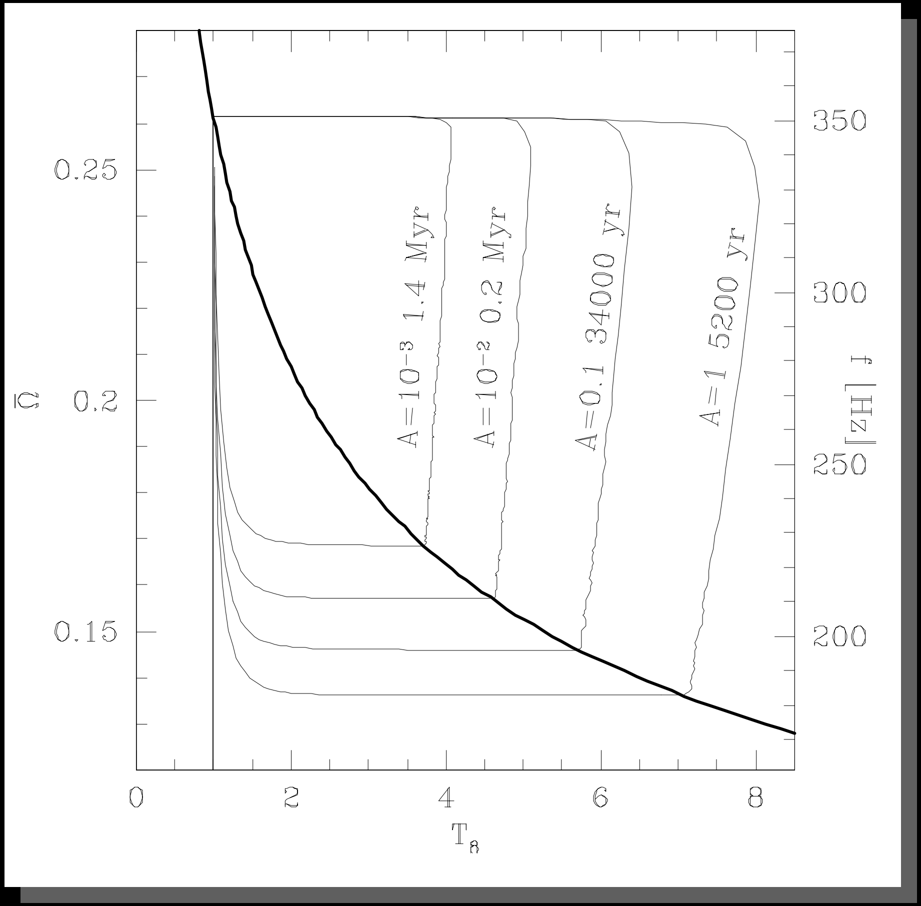
- Viscosity damps fluid motions. Its effects are strongest for small wavelengths.
- Even a large scale mode has a large gradient in a boundary layer.
- Intermode coupling



Arras et al. '02

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.



JSH '02

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.