PERSISTENT GRAVITATIONAL RADIATION: SOURCES AND LIGO DETECTION

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Persistent sources: slowly varying frequency

Initial major focus: accreting neutron stars

Parameterized model → detection templates

Other directions:

Recently formed neutron stars (same approach)

Search for scalar (spin zero) gravitational waves

Requested support: one month summer salary, one graduate student, ...

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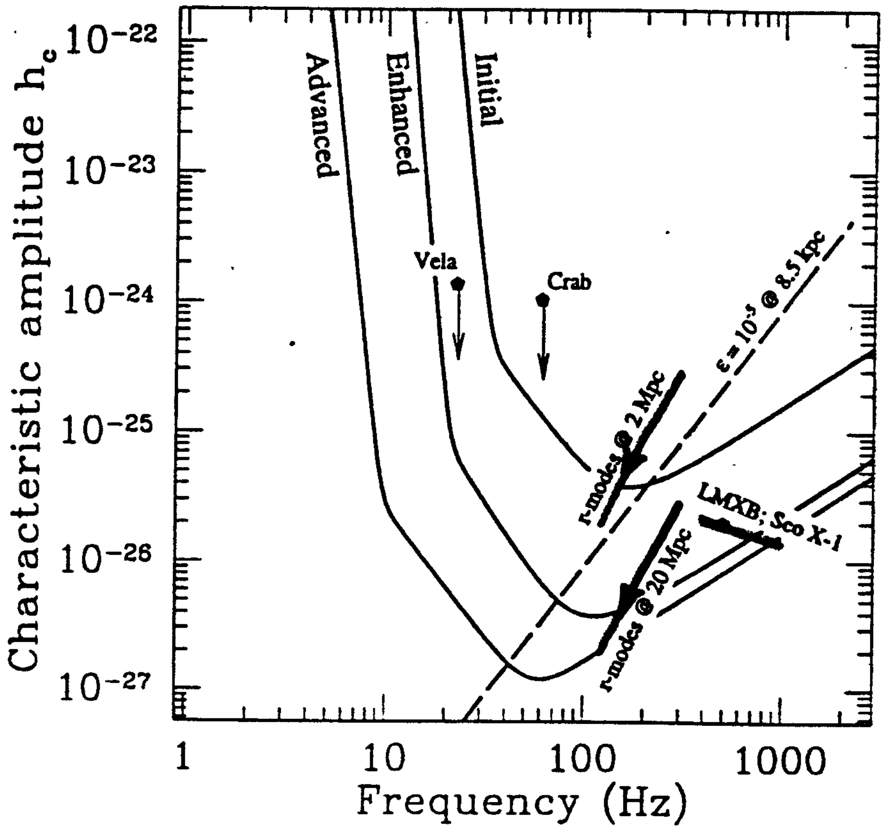


FIG. 3. Characteristic amplitudes h_c [see Eq. (3.5) in [1]] for several postulated periodic sources, compared with sensitivities $h_{3/\mathrm{yr}}$ of the initial, enhanced and advanced detectors in LIGO. ($h_{3/\mathrm{yr}}$ corresponds to the amplitude h_c of the weakest source detectable with 99% confidence in $\frac{1}{3}\mathrm{yr} = 10^7\mathrm{s}$ integration time, if the frequency and phase of the signal, as measured at the detector, are known in advance.) Long-dashed lines show the expected signal strength as a function of frequency for pulsars at a distance of 8.5 kpc assuming a gravitational ellipticity $\epsilon = 10^{-5}$ of the source (see Ref. [1]). Upper limits are plotted for the Crab and Vela pulsars, assuming their entire measured spindown is due to gravitational wave emission. The characteristic amplitude of waves from r-modes is also shown. These signals are not precisely periodic; rather, they chirp downward through a frequency band of $\sim$ ~~1~~00 Hz 5
10^4 in 2×10^7 seconds. Finally, the strength of the gravitational waves from LMXB's, normalized to the observed x-ray flux from Sco X-1, is plotted under the assumption that gravitational waves are entirely responsible for their angular momentum loss.

Brady + Creighton (1998)

LSC Data Analysis White Paper

5 CW Source Searches

CW Source Searches

	Directed known phase	Data base	FFT stack/slide Hierarchical	Hough Transform Hierarchical	Robust Algorithms	Discriminators	Multiple Detector Analysis
Priority	1	1	1	1	3	1	2
FTE (Code+Test)	2+2	?	6+6			TBD	
FTE (Science)			1		TBD		1
AEI		L		L			
Cardiff			I				
Caltech	L		I				
Michigan	I					L	
Stanford					L		I
UWM			L				

Table 3: Tasks and group assignments for CW (pulsar) source searches. FTE's in person-months. L=lead group, I=interested group.

Priority 1 tasks are essential and must be completed by November 2000.

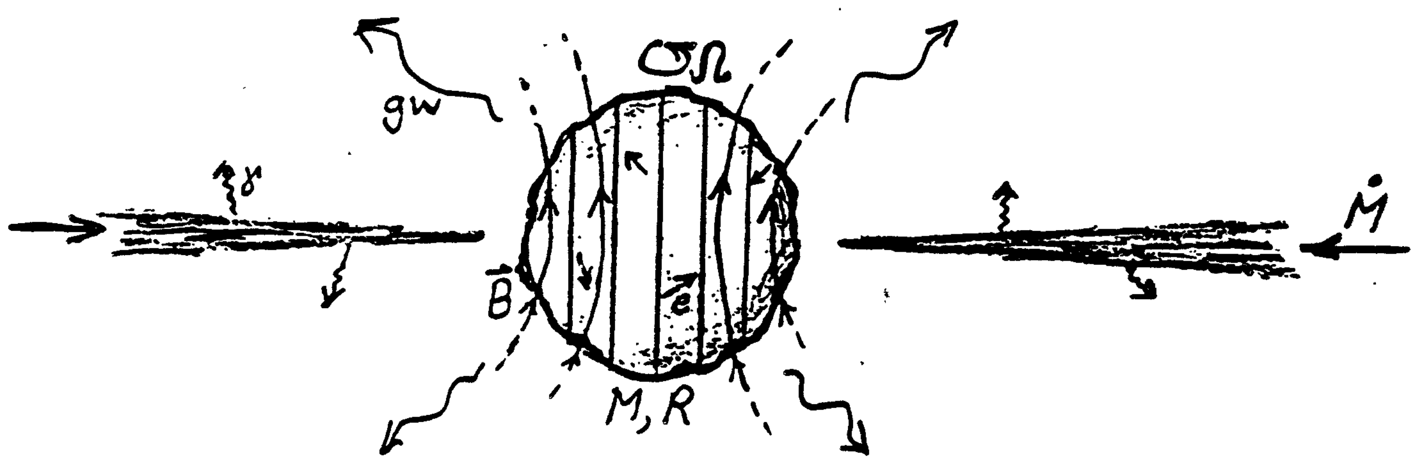
Priority 2 tasks are useful, and should be completed by November 2001.

Priority 3 tasks are research.

One of the ASIS task tables

Robust Algorithms involve "specialized methods capable of searching for (such) waves from poorly modeled sources".

NEUTRON STARS IN X-RAY BINARIES



- Weak magnetic field required
- Types of perturbation:

  A) r-mode (Coriolis–driven velocities)

  B) temperature–induced inhomogeneous electron–capture

  C) ?
- Targets: known LMXBs, position from X-ray (and optical) observations.
- Orbital radial velocity, period, and phase estimated from optical observations.
- Frequency $f_{gw} = F(\Omega)$ estimated from X-ray observations.
- Varying accretion rate $\dot{M}$ produces small, rapid changes in Ω (one cycle in at least ~ 3 days).
- Use stacking of power spectra within a hierarchical strategy (Brady & Creighton).
- Signal–recycled narrow–band detection mode produces enhancement of 5-10.

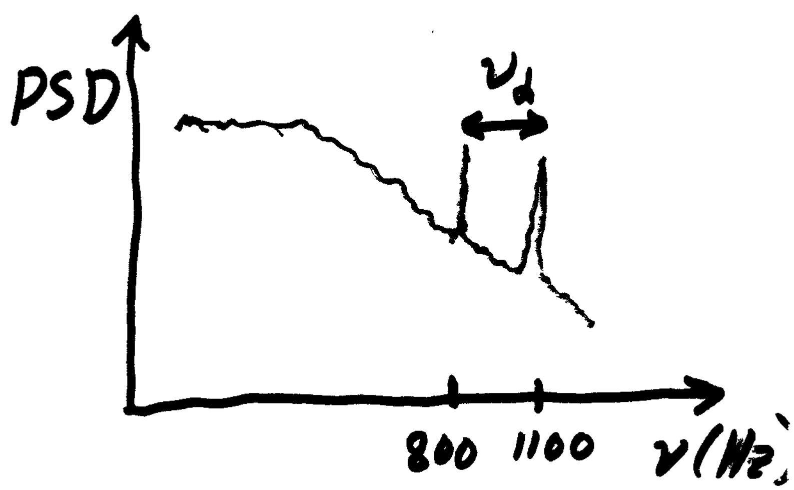
RXTE Detection of Neutron Star Spin in LMXBs

Table 1: Rapid Periodicities During Type I X-Ray Bursts

Object Name	ν_B (Hz)	ν_d (Hz)	Flux[a]	h_c (10^{-27})	Ref.[b]
4U 1702-429	330	–	1.0	1.2	[1]
4U 1728-34	363	363	2.8	2.0	[2]
KS 1731-260	524	260 ± 10	0.2-2	2.0	[3-4]
Aql X-1	549	–			[5]
4U 1636-53	581	276 ± 10	4.4	2.8	[6-7]
MXB 1743-29	589	–			[8]

Bildsten 1998

[a] Average 2-10 keV fluxes (in units 10^{-9} erg cm^{-2} s^{-1}) are from van Paradijs (1995).
[b] REFERENCES: [1] Swank et al. 1997, [2] Strohmayer et al. 1996, [3] Smith et al. 1997, [4] Wijnands & van der Klis 1997, [5] Zhang et al. 1998a, [6] Strohmayer et al. 1998, [7] Wijnands et al. 1997, [8] Strohmayer et al. 1997a



Burst signal (ν_b) is coherent.

EVOLUTION OF ACCRETING (or newborn) NEUTRON STARS

Two-component model of star (Owen et al. 1998):

$$J(\Omega, \alpha) = I\Omega + \tilde{J} = I\Omega(1 - K_j\alpha^2)\ , \quad (\alpha^2 \ll 1,\ K_j \sim 1)\ .$$

Conservation of angular momentum:

$$\frac{dJ}{dt} \cong \ell_a \dot{M}(t) - \left(\frac{dJ}{dt}\right)_{gw}\ , \tag{1}$$

where

$$\left(\frac{dJ}{dt}\right)_{gw} = \frac{m}{\omega}\left(\frac{dE}{dt}\right)_{gw} = \alpha^2 I\Omega F_j(\Omega)\ .$$

Rate of change of energy of perturbation (in rotating frame):

$$\frac{d\tilde{E}}{dt} = 2\tilde{E}\left(\frac{1}{\tau_{gw}} - \frac{1}{\tau_{vis}}\right)\ , \tag{2}$$

where

$$\tilde{E} = K_e\alpha^2 I\Omega^2\ , \qquad \tau_{gw}^{-1} = F_e(\Omega)\ , \quad \tau_{vis}^{-1} = F_v(\Omega, T)\ .$$

Thermal energy conservation:

$$C_v(T)\frac{dT}{dt} = \frac{2\tilde{E}}{\tau_{vis}} + \varepsilon\langle\dot{M}\rangle c^2 - L_{\gamma,int}(T) - L_\nu(T)\ . \tag{3}$$

Accretion energy conservation:

$$L_\gamma \cong (3GM/4R)\dot{M}(t)\ . \tag{4}$$

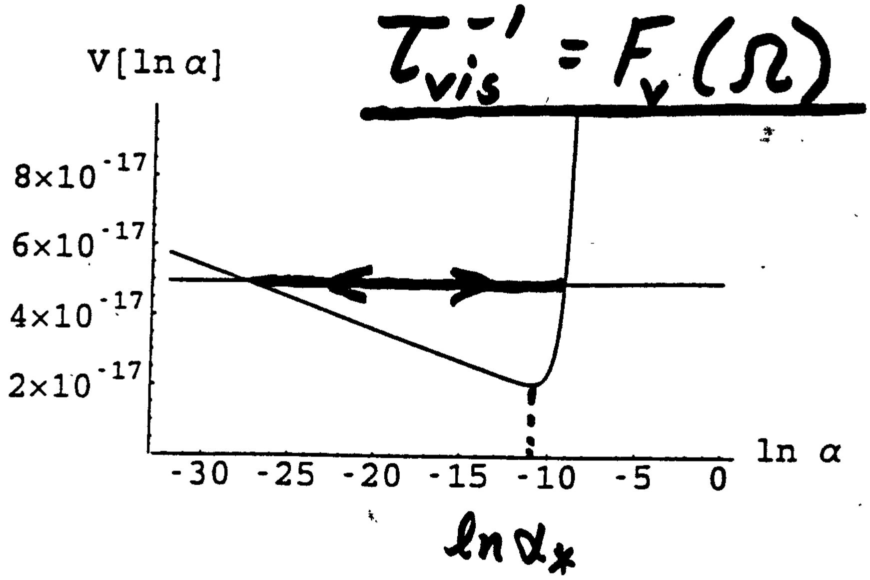
The evolution equations (1), (2), and (3) can be combined into the set

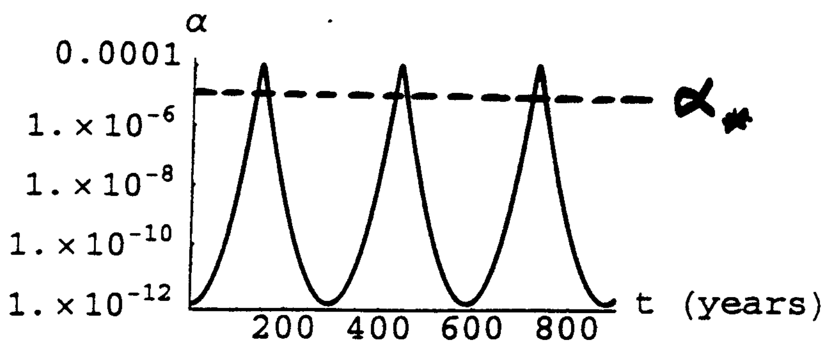
$$\frac{d\alpha}{dt} = f_1(\alpha, \Omega, T) \ , \quad \frac{d\Omega}{dt} = f_2(\alpha, \Omega, T) \ , \quad \frac{dT}{dt} = f_3(\alpha, \Omega, T) \ .$$

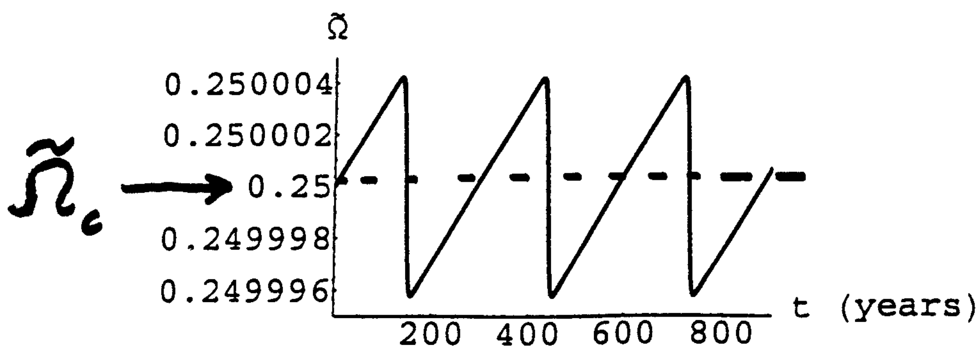
For a steady state ($dJ/dt = 0$), equations (1) and (4) give the gw amplitude

$$h \approx 4 \times 10^{-27} \left(\frac{F_\gamma}{10^{-8} \text{ erg cm}^{-2} \text{ s}^{-1}} \right)^{1/2} \left(\frac{f_{gw}}{600 \text{ Hz}} \right)^{-1/2} \ .$$

Equilibrium can be unstable.
(Wagoner + Hennawi 1999)


$\tau_{vis}^{-1} = F_\nu(\Omega)$
V[ln α]
8×10^-17
6×10^-17
4×10^-17
2×10^-17
-30 -25 -20 -15 -10 -5 0
ln α
ln α_*


α
0.0001
1.×10^-6
1.×10^-8
1.×10^-10
1.×10^-12
α_*
200 400 600 800
t (years)


Ω̃
0.250004
0.250002
0.25
0.249998
0.249996
$\tilde{\Omega}_c$
200 400 600 800
t (years)

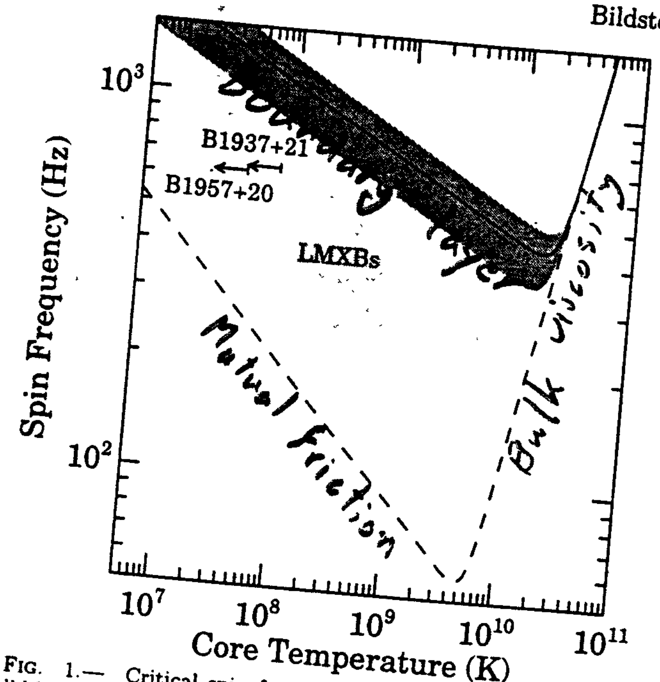


FIG. 1.— Critical spin frequencies for the r-mode instability. Solid line shows the critical frequency set by the viscous boundary layer and internal dissipation, for a star with normal nucleons in the core. The shading around the solid line displays the effect of core superfluidity. The dashed line shows the critical frequency as calculated previously, neglecting the boundary layer friction. The LMXBs reside in the rectangular shaded region. The arrows show the frequencies and the upper limits on core temperatures (obtained, as in Andersson et al. 1999b from Reisenegger 1997 and Gudmundsson et al. 1982) of the two fastest known MSPs.

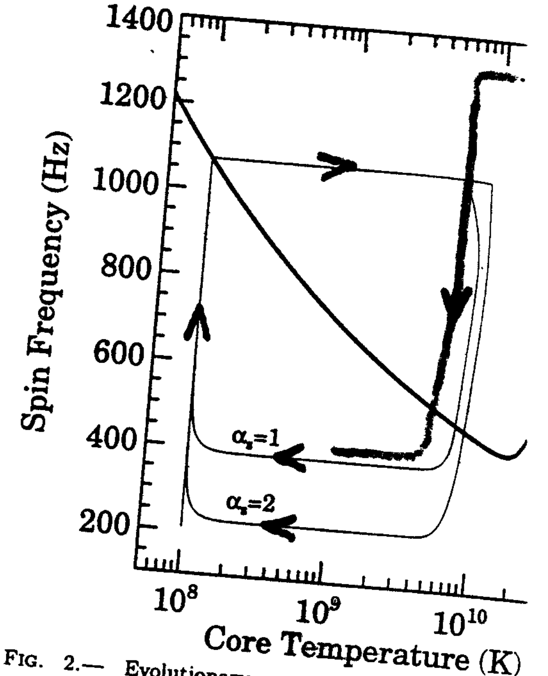


FIG. 2.— Evolutionary scenarios for rapidly rotati stars with crusts. The thick solid line shows the critic quency for the r-mode instability, including boundary lay The two thin solid loops show the evolution of a neutron LMXB, accreting at $10^{-8} M_\odot$ yr^{-1}, for two different val r-mode saturation amplitude α_s, as marked on the plot. T line shows the spin-down and cooling of a newborn rapidl neutron star.

LMXBs

Spinup: 5×10^6 yr

Radiating: < 1 yr

Cooldown: 10^5 yr

Newborn neutron star

Radiating (spindown): 10^4 sec

UNCERTAINTIES IN NEUTRON STAR PHYSICS

1) The neutrino luminosity $L_\nu(T)$. (Core and crust)

2) The heat capacity $C_v(T)$ and equation of state.

3) The superfluid transition temperature T_c. ($6\times10^{8-9}$ K)

4) The spatial and time dependence of the temperature.

5) The viscous damping rate $F_v(\Omega, T)$. (most critical)

6) The fraction ε of the accreted rest-mass energy that heats the crust.

7) The relation between gravitational wave frequency and neutron star angular velocity.

Approach: embed the range of uncertainties within a parameterized description.

NEWBORN NEUTRON STARS

- Supernova gives position (rate ~ 0.5/year within 8 Mpc).
- Born hot and rapidly rotating.
- R-mode amplitude and frequency evolution uncertain (non-linear hydrodynamics).
- Gravitational wave emission phase lasts

  a) 10^7 seconds, down to a frequency $f_{gw} \approx 160$ Hz (Owen et al. 1998),

  b) 10^4 seconds, down to a frequency $f_{gw} \approx 550$ Hz (Bildsten & Ushomirsky 1999).

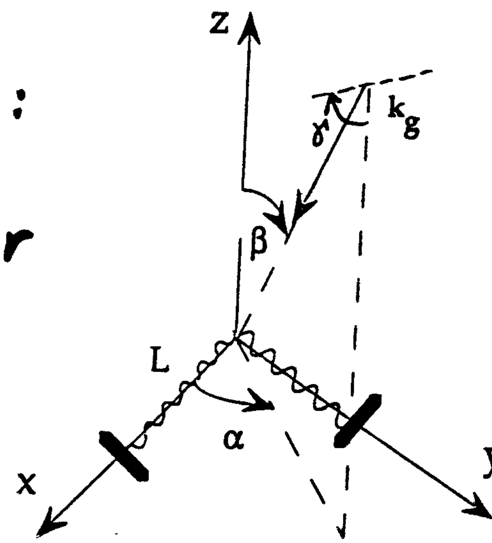
PHASE SHIFTS IN SPIN 0,2 GRAVITATIONAL WAVE

- *Persistent source:*

  Single detector

- *Burst source:*

  Multiple detectors



Assume $\lambda_{gw} = 2\pi/k_g \gg L$. Laser wavelength is λ.
Relative spin 0 (φ) coupling constant $a^2 < 0.0005$, in theories obeying the equivalence principle.

A) Difference mode phase shift:

$$\Delta\Phi_1 - \Delta\Phi_2 = (2\pi L/\lambda)\{2a\sin^2\beta\cos(2\alpha)\varphi(t) + [2\cos\beta\sin(2\alpha)\sin(2\gamma) - (1+\cos^2\beta)\cos(2\alpha)\cos(2\gamma)]h_+(t) - [2\cos\beta\sin(2\alpha)\cos(2\gamma) - (1+\cos^2\beta)\cos(2\alpha)\sin(2\gamma)]h_\times(t)\}\,.$$

B) Common mode phase shift (relative to laser):

$$\Delta\Phi_1 + \Delta\Phi_2 = (2\pi L/\lambda)\{-2a(2-\sin^2\beta)\varphi(t) + \sin^2\beta[\cos(2\gamma)h_+(t) - \sin(2\gamma)h_\times(t)]\}\,.$$