# Gravitational Radiation from Accreting Neutron Star X-ray Sources: Modeling and LIGO Data Analysis

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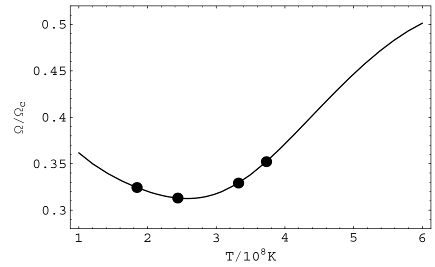
## Background

- Spin frequencies of low-mass X-ray binary (LMXB) neutron stars pile up below 619 Hz; for radio pulsars, below 642 Hz. Most neutron star models can spin at least twice as fast. This provides some evidence that gravitational radiation has halted their spin up (Bildsten 1998).
- In equilibrium, the gravitational wave (GW) flux is proportional to the X-ray flux (proportional to the accretion rate) (Wagoner 1984). The neutron star converts accreted angular momentum to radiated angular momentum.
- This proposal complements that of the Stanford Advanced Gravitational Wave Interferometry Group. Research and outreach efforts will be coordinated with them, aided by Stanford's Office of Science Outreach.

## **Recent Research** (NSF PHY-0070935)

- Developed a computer program to follow the evolution of the r-mode velocity amplitude, spin frequency (***f***), and core temperature of an accreting neutron star. Gravitational-wave frequency $f_{GW}$ is approximately 4***f***/3.
- Neutrons normal in core, superfluid in inner crust; protons superfluid in core. Inferred from cooling of isolated neutron stars (Kaminker et al. 2002).
- Included all relevant damping (core-crust boundary layer shear viscosity and hyperon bulk viscosity), neutrino emission processes, and external (mass accretion and magnetic coupling) torques.

- Proved that there is a thermal runaway (Levin 1999) from any negative slope section of the critical curve (Fig. 1), and stable slow evolution (time scale > $10^7$ years) along any positive slope portion. Showed that hyperon bulk viscosity can produce a stable portion if its superfluid transition temperature is low.
- Showed that during the “quiescent” phase of transient LMXB neutron stars, the constant gravitational radiation spin down rate (Fig. 4) is comparable to that detected (SAX J1808.4-3658 and XTE J0929-314). (But spin up also seen.)



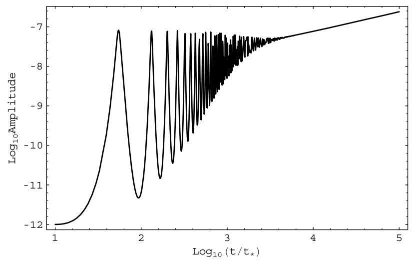
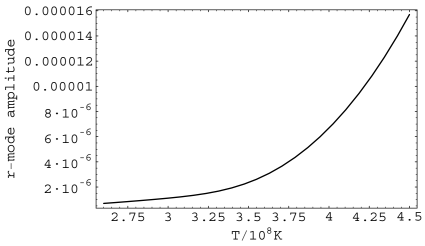


Fig. 1. The relation between the (fractional) angular velocity (2/3 at breakup) and the core temperature on the critical curve, for a hyperon superfluid transition temperature $T_h$ = $10^9$ K. On the critical curve, the gravitational radiation induced growth rate of the mode (proportional to $f^6$) equals its viscous damping rate. The initial (left) and equilibrium (right) states are shown for moderate (left pair) and high (right pair) accretion rates.

Fig. 2. Early evolution of the (fractional) r-mode amplitude, after spin up to a stable section of the critical curve.



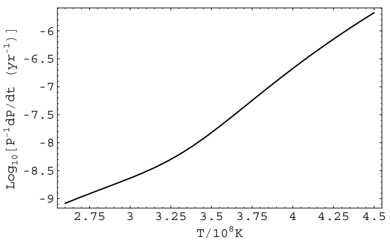


Fig. 3. The r-mode amplitude ($\alpha$) on the stable section of the critical curve, when r-mode heating dominates accretion-induced heating. The gravitational wave strain $h$ is proportional to $f^3\alpha$.

Fig. 4. The spin down rate produced by gravitational radiation, on the stable section of the critical curve.

## **Proposed Research**: Source modeling

- Improve calculations of hyperon bulk viscosity (with Ben Owen) and boundary layer viscosity.
- Improve calculations of the relativistic and spin corrections to $f_{GW}(f)$ (with Ben Owen).
- Include the radial dependence of the neutron star interior temperature, and determine the surface X-ray luminosity. The contribution of r-mode heating to the “quiescent” luminosity of transient LMXBs (Brown & Ushomirsky 2000) can then be better determined. This is the second signature of gravitational radiation possible in this class of X-ray sources.

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- Improve calculations of the magnetic coupling between the neutron star and its accretion disk (with Wynn Ho). The goal is to separate the (accretion-rate dependent) contribution of this magnetic torque to any observed change in spin rate from the constant contribution due to gravitational radiation (the first signature).
- Follow the evolution to the critical curve after the r-mode saturates (at a small amplitude, Arras et al. 2003) during a thermal runaway.

## **Proposed Research:** Data analysis

- Development of algorithms, based upon Brady & Creighton (2000):
  - Stacking of power spectra
  - Search near parameters of candidate signals identified from lower threshold searches.
  - Binary orbit parameters comprise one set, constrained by observations of companion star.

We will study the approach of Alberto Vecchio's group to the analysis of LIGO I data (for Sco X-1, ...). Involvement with the LSC periodic source data analysis group will be important.

- Encourage more observations of targets: LMXB neutron stars with high spin rates, observed (during bursts or continuously) or inferred (from high-frequency QPO splitting).
  - a) Steady bright sources (like Sco X-1; search for its spin period)
  - b) Transient bright sources (which could be spinning down or up)

Collaboration with Deepto Chakrabarty is important.

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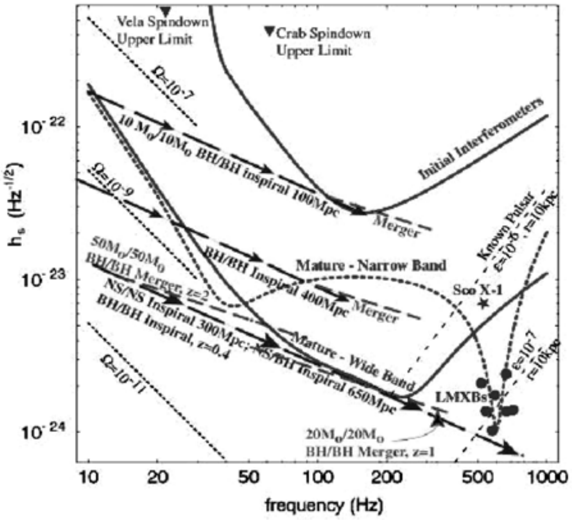
- Models [$\alpha(t), f(t), T(t)$] → observables [phase $\int f_{GW}(t)\,dt$ and amplitude $h(t)$]. We will also search at $f_{GW} = 2f$ (fixed quadrupole moment). The phase can vary by one cycle after at least 3 days due to a fluctuating accretion rate. Monitoring X-ray flux can help; we will investigate.

- Try to better understand the evolutionary relationship between X-ray and radio pulsar spin frequencies.

- Investigate the optimal use of signal recycling (narrow-banding) in Advanced LIGO for these sources. What should be the target frequency? For what time period should it be employed?

- We will provide an updated estimate of GW strain amplitudes for both steady and transient sources. Improved estimates of average accretion rates (from RXTE ASM data) will be employed.

## Advanced LIGO



Estimates (Bildsten) for LMXBs assume

a) equilibrium

b) $f_{GW} = 2f$

c) $f = \Delta f_{QPO}$

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## Personnel

- **Principal Investigator** (25% effort): Robert Wagoner, Professor of Physics, Emeritus. Source modeling and supervision of data analysis.
- **Co-Investigator** (10% effort): Brian Lantz, Physical Sciences Research Associate. Characterization of the detectors and input to data analysis.
- **Co-Investigator** (10% effort): Norna Robertson, Physical Sciences Research Associate. Characterization of the detectors and input to data analysis.
- **Postdoctoral Research Affiliate** (50% effort): Wynn Ho, KIPAC Hubble Fellow. Source modeling and development of data analysis algorithms.
- **Postdoctoral Research Affiliate** (100% effort): To be hired. Production of algorithms and search for signals in LIGO data.
- **Graduate Student Research Assistant** (50% effort): To be hired. Contribution to source modeling and data analysis.
- **Undergraduate Student** (Variable effort, supported mostly by Stanford): To be hired. Assist with computer programming and data analysis.

## Collaborators

- **Data analysis**: Alberto Vecchio (University of Birmingham)
  Patrick Brady (University of Wisconsin, Milwaukee)
- **Theoretical physics and modeling**: Ben Owen (Center for Gravitational Wave Physics, Penn State University).
- **Observational X-ray astronomy**: Deepto Chakrabarty (Center for Space Research, M.I.T.)

## KIPAC Resources

The Kavli Institute for Particle Astrophysics and cosmology (KIPAC) at Stanford University (founded in 2003) provides a stimulating environment, and supports this research effort.

- Nine new joint (Physics Dept./SLAC) faculty, 5 to be hired. Director: Roger Blandford, Deputy Director: Steven Kahn.
- Existing physics faculty member Roger Romani also involved in neutron star astrophysics.
- Presently 12 postdoctoral researchers. Chandra Fellow Anatoly Spitkovsky numerically investigates surfaces and magnetospheres of neutron stars.
- Main KIPAC building at SLAC and additional building to partially house KIPAC on campus to be completed in 2006.
- Computing and numerical simulation center to be a key ingredient of SLAC site. Headed by new faculty member Tom Abel.

# Conclusions

- LIGO may provide a powerful probe of the extreme conditions within neutron stars, especially:
  - a) Superfluid transition temperatures
  - b) Presence of hyperons
  - c) Strong gravitational fields
  - d) Rapid rotation

- Data analysis is greatly aided by use of X-ray and optical observations.

- LIGO signal recycling is critical for detection.