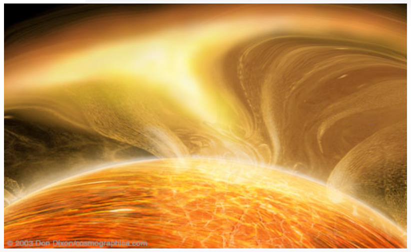
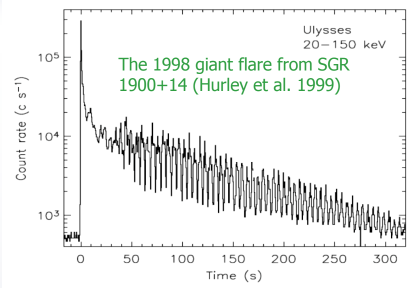
The Joint Institute for Nuclear Astrophysics

Magnetar Seismology

Anthony L. Piro

University of California, Santa Barbara





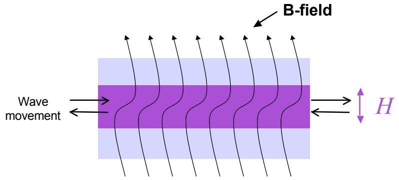
Introduction

Soft gamma-ray repeaters (SGRs) are characterized by their short (0.1 sec) recurrent bursts of soft gamma-rays. They have been successfully explained as neutron stars with super-strong magnetic fields (10^{15} G); the magnetar model of C. Thompson and R. Duncan. In addition to their normal bursts that release approximately 10^{41} ergs of energy, there have been three "giant flares" that released 10^{44}-10^{46} ergs in a matter of minutes. Not only do the giant flares show large pulsations at each SGR's spin period (5-8 sec), but they also show multiple higher frequency oscillations in the range of 18-155 Hz. The thrilling implication is that these oscillations may be shear modes, excited from crustal deformations during the flare (Duncan 1998). If true, they would be the first modes ever seen from a neutron star, initiating a new era where seismology is used to learn about neutron star crusts.

We focus on oscillations that are trapped in the magnetar crust and find two set of modes:

1. Modes with at least one radial node. These are strongly sensitive to the strength of the magnetic field and have a wavelength set by the crusts thickness.

Toy model of the solid crust sandwiched between the liquid ocean and core with a vertical magnetic field:



Both the B-field and shear modulus resist the wave's movement, thus the frequency estimate includes both the Alfven and shear speeds:

$$\omega \approx \frac{(v_s^2+v_A^2)^{1/2}}{\lambda} \sim (v_s^2+v_A^2)^{1/2}\frac{n}{H}$$

2. Modes with at no radial nodes (transversely propagating). These are less sensitive to the strength of the magnetic field because the shear modulus is so strong at the base of the crust. Their wavelength is set by the radius.

The vertical magnetic field is no longer sheared, so only the shear modulus acts as a restoring force. Thus only the shear speed comes into the frequency estimate. This directly shows how the frequency depends on the density and composition of the crust.

$$\omega \approx \frac{v_s}{\lambda} \approx v_s\frac{\sqrt{l(l+1)}}{R}$$

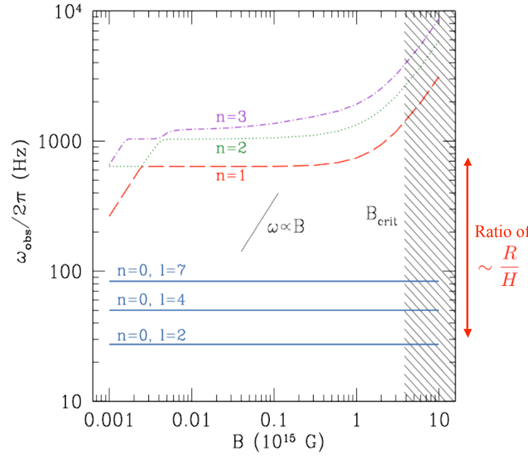
$$\left.\frac{\omega_{obs}}{2\pi}\right|_{n=0} = 28.8\ \mathrm{Hz}\ \rho_{14}^{1/6}\left(\frac{Z}{38}\right)\left(\frac{302}{A}\right)^{2/3}\left(\frac{1-X_n}{0.25}\right)^{2/3} \times R_{12}^{-1}\left(1.53-0.53\frac{M_{1.4}}{R_{12}}\right)^{1/2}\left[\frac{l(l+1)}{6}\right]^{1/2}$$

Full calculations with a realistic crust model

Using the models of Haensel & Pichon (1994) and Doucin & Haensel (2001) we perform full calculations of the torsional modes, assuming that they are trapped above the core.

These results confirms our earlier estimates. There are two set of modes, with the higher frequency mode more sensitive to the magentic field.

Also, the ratio of the two set of frequencies is equal to the **ratio of the radius to crust's thickness**.



Our Calculation

We performed detailed calculations of torsional oscillations of magnetized neutron stars using a simple radial magnetic field and plane parallel geometry (see figures). The calculations demonstrate that the observed pulsations are well explained by low radial-order oscillations, and also show how these waves depend on the neutron stars' mass, radius, and crustal composition. Oscillations with shorter radial wavelengths have higher frequencies (~600-2000 Hz), and are useful for further investigation of the crust. In fact, subsequent analysis of the December 2004 flare using the RHESSI satellite found a pulsation with a frequency of 626.5 Hz (Watts & Strohmayer 2006), consistent with our predictions for the next higher order shear wave. *This result is strong evidence that the oscillations are crustal in origin!*

Future Prospects

These calculations are just an initial step in using seismology to learn about these exotic environments. Future studies should consider more realistic magnetic field geometries and how they alter the frequencies (Messios et al. 2001). We have ignored magnetic coupling between the crust and other portions of the neutron star (Levin 2006). A calculation of the transmission of waves through the ocean and into the magnetosphere (Blaes et al. 1989) would be key for understanding the emission mechanism. Relating this to the observed coherence of the oscillations (Q~20-50), could provide an additional, powerful constraint.

Main reference: A. L. Piro, 2005, *Ap. J. L.*, **634**, L153

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