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Neutron star oscillations and instabilities: Lecture 2

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1 INTRODUCTION

In Lecture 1 we talked about the general principles of mode calculation, and looked at some of the global modes of the fluid core of most interest to gravitational wave detectors. In this Lecture we will look at two different phenomena that have been observed by electromagnetic means. In both cases a very rapid instability of one kind seems to trigger oscillations of a different kind in the star. In the first case we understand the trigger instability quite well, but not the resulting oscillations - in the second we understand the resulting oscillations much better than the trigger instability!

I will refer to the slides by number for various graphics.

2 THERMONUCLEAR INSTABILITIES AND OSCILLATIONS

2.1 Thermonuclear instability

Slide 2 shows a artist's impression of an accreting neutron star in a binary system. The companion star (to the right) is filling its Roche lobe and losing matter into an accretion disk around the neutron star. Matter makes its way through the disk and eventually falls onto the surface of the neutron star.

What then happens to the accreted matter as it settles in the neutron star ocean (the layers above the crust)? It starts to undergo thermonuclear reactions as it is compressed and heated. H, for example, burns to He, and He burns to form C. The potential energy release (200 MeV/nucleon) due to accretion vastly exceeds the energy released by steady state burning (7 MeV/nucleon for H burning to He). This means that to see the surface processes we have to wait for unstable burning, when the energy release is much faster. Fortunately, nature obliges in the form of X-ray bursts.

Slide 3 shows time lapse images taken over 100s by the Einstein X-ray Observatory. You can see the brightness of one of the sources increase and then fade away again very rapidly. This is an X-ray burst.

Slide 4 shows the lightcurves of some typical X-ray bursts from different sources. The shapes vary a little, depending on the ratio of H/He in the accreted material, but typically bursts last 10-100s.

So what is going on here (Slide 5)? An X-ray burst is essentially a thermonuclear runaway, or unstable nuclear burning. To see why such an instability might occur, consider the balance between the heating process (the nuclear burning) and the cooling process (radiative losses). The rate of cooling (via blackbody radiation) is temperature dependent. If the heating process is also temperature dependent then the potential for instability exists - if a small perturbation upwards in temperature causes the heating rate to increase far more than the cooling rate then we get a thermonuclear runaway!

It turns out that both H and He have temperature dependent nuclear burning. At low temperatures (which in practice means low accretion rates), H burns via the CNO cycle, where the rate limiting step from ^{14}N to ^{15}O is temperature-dependent. At higher temperatures H burning happens via the hot CNO cycle - in this reaction the rate limiting steps are beta decays which are temperature independent, so at high accretion rates H burning is actually stable. He burning, of course, occurs via the strongly temperature dependent triple alpha reaction.

It turns out that at the lowest accretion rates, all burning is stable. As accretion rate increases, H ignition goes unstable, and then stabilises again. As we increase accretion rate still further, He burning becomes unstable. At the highest accretion rates, however, this process also stabilises because cooling becomes more efficient again. The different ignition regimes give rise to different types of X-ray bursts. In addition to the 'normal' bursts we now also know about long bursts (Slide 6) which are seen in cold neutron stars that accrete only He, and superbursts (Slide 7), which are due to unstable C burning. It turns out that C burning can also be temperature dependent under certain conditions! Because C burning happens deep in the ocean of the star, the thermal timescale for radiation to escape is long, hence the long duration of superbursts.

This type of thermonuclear instability is essentially just a very rapidly exponentially growing oscillation. This is made clear by the existence of marginally stable burning right on the boundary of stability (Slide 8). A little lower in accretion rate and burning is stable, a little higher and you get real X-ray bursts - and right at the boundary accretion rate you see beautiful oscillatory behaviour!

2.2 Thermonuclear oscillations?

There are over 100 accreting neutron stars that have X-ray bursts. Around 10% of these also show what are called burst oscillations (Slide 9). These are periodic, high frequency variations in brightness seen during X-ray bursts. The frequency drifts a little bit, but is close to the spin frequency of the neutron star. The star in Slide 9 is also a pulsar, so the spin frequency, marked as a dashed line, is known. The contours show the frequency and strength of the burst oscillation as it drifts upwards in frequency.

What causes this phenomenon is not yet understood. Essentially (Slide 10) we need part of the stellar surface to get hotter than the rest during the thermonuclear explosion. As the star spins we would then see periodic variations in X-ray brightness at the spin frequency. The fact that the frequency drifts a little means that we need this hot patch to move a little on the surface of the star.

The most promising models to explain the phenomenon involve the excitation, by the thermonuclear flame front, of global modes in the ocean layers of the neutron star. The resulting variations in ocean height could give rise to the temperature pattern that we see. What type of ocean mode might be responsible is not yet known - various possibilities, including r-modes and shearing modes, are being studied (Slide 11 shows temperature patterns associated with some of these oscillations). If we can eventually identify and model the modes correctly, burst oscillations would teach us about the surface layers of the neutron star.

3 MAGNETIC-ELASTIC INSTABILITIES AND OSCILLATIONS

3.1 Magneto-elastic instability?

Magnetars (Slide 13) are a small class of neutron stars with exceptionally high magnetic fields ($\sim 10^{15}$ G). This field strength is so strong the field would drag around the star's crust (due to the charged particles in the crust) as it moves.

Magnetars emit regular short gamma-ray flares, lasting 0.1-1s (Slide 14 shows some examples). When active they can emit hundreds of these flares over periods of hours. The underlying cause of the flares is thought to be decay of the strong magnetic field, which twists and tangles, eventually reconnecting, triggering particle acceleration and high energy emission. However the instability that triggers the reconnection is not yet known. One possibility is that the solid crust resists field motion, which can only occur when the crust ruptures under the stress - an elastic instability. The other possibility is that the crust yields more easily, but that stress builds up in the external magnetosphere. Only when a plasma instability develops in the magnetosphere does reconnection occur.

3.2 Magneto-elastic oscillations

On rare occasions, magnetars emit much more energetic giant flares, which last far longer. Slide 15 shows the lightcurve of one such event - the slow pulsations that develop in the tail of the giant flare are at the rotation period of the star. Giant flares are thought to be due to huge, global magnetic reconnection events. They are so energetic that they form huge quantities of plasma, which gets trapped by the field (see inset) - as the star rotates these swing past our line of sight giving pulsations at the spin period which last until the plasma evaporates several hundred seconds later.

The giant flare from the magnetar SGR 1806-20, at the end of 2004, revealed a surprise - high frequency variations in the lightcurve during the decaying tail. Slide 16 shows a power spectrum with the two strongest oscillations - at 90 Hz and 625 Hz. Several more frequencies were also found - Slide 17 shows the times over which they seemed to be most active. Looking back at the data from the 1998 giant flare from the magnetar SGR 1900+14 then revealed similar high frequency oscillations. The frequencies ranged from 18 Hz up to 1800 Hz!

It had long been predicted (Duncan 1998) that giant flares might be sufficiently violent to excite toroidal shear modes of the neutron star crust - twisting motions whose frequency depends primarily on the shear speed in the crust. Comparing to simple models (of the type that we computed in Lecture 1, but including the solid crust), the frequencies were an extremely good match! The various frequencies were identified with different angular and radial harmonics of the shear modes. The lowest frequencies were then identified with twisting Alfven modes of the neutron star core.

Better modelling, taking into account more physics ingredients, is now underway - however these magnetar observations certainly seem to be the first direct detection of seismic vibrations in a neutron star. This means that we can now start to do seismology.

The mode frequencies depend, amongst other things, on the mass and radius of the neutron star. Radius and crust thickness (which depends on mass and radius) set the overall resonant cavity size (frequency is inversely proportional to cavity size) for the different harmonics. Correct identification of the fundamental frequency and the first radial overtone would allow us to put very tight constraints on mass and radius, and hence the dense matter equation of state. Slide 19 shows how these modes give complementary constraints for a fundamental at 29 Hz and an overtone at 625 Hz (including some uncertainty from the observations). The star must lie, for this simple oscillation model, within the grey box. The coloured lines are various different equations of state, shown for comparison. We know that this is not the final answer since there are many other pieces of physics that need to feed into our models - but it shows the potential of seismology in the study of neutron star physics!

4 FURTHER READING

X-ray bursts and burst oscillations

Thermonuclear Burning on Rapidly Accreting Neutron Stars, L. Bildsten, page 419 in NATO ASIC Proc. 515: The Many Faces of Neutron Stars, eds. Buccheri, van Paradijs and Alpar (1998).

New views of thermonuclear bursts, T.Strohmayer & L.Bildsten, in Compact stellar X-ray sources, Edited by Walter Lewin & Michiel van der Klis. Cambridge Astrophysics Series, No. 39, Cambridge University Press, p. 113 - 156 (2006)

Magnetar flares and oscillations

Soft gamma repeaters and anomalous X-ray pulsars: magnetar candidates, P.M.Woods & C.Thompson, in Compact stellar X-ray sources, Edited by Walter Lewin & Michiel van der Klis. Cambridge Astrophysics Series, No. 39, Cambridge University Press, p. 547 - 586 (2006)

Neutron star oscillations and QPOs during magnetar flares, A.L.Watts & T.Strohmayer, Advances in Space Research, 40, 1446-1452 (2007)