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Extreme aspects of neutron star low-mass X-ray binaries

Sudip Bhattacharyya*
Department of Astronomy and Astrophysics, Tata Institute of Fundamental Research, Mumbai, India

Abstract. Here, we discuss three features, viz., thermonuclear X-ray bursts, broad relativistic iron lines and kilohertz quasi periodic oscillations, of accreting neutron stars. These features can be useful for probing extreme environments, and to test fundamental laws of nature.

Keywords : dense matter – equation of state – relativity – stars: neutron – X-rays: binaries

1. Introduction

Neutron stars provide a unique opportunity to probe extreme environments. Here we discuss three observational features of neutron star low-mass X-ray binaries (LMXBs), which can be useful for such probing.

2. Thermonuclear X-ray burst

Sudden increase of X-ray intensity is observed from many neutron star LMXB systems every few hours to days (Strohmayer & Bildsten 2006, and references therein). These are called type-I X-ray bursts. The observed intensity sharply increases typically by a factor of ~ 10 in $\approx 0.5 - 5$ seconds, and then decreases relatively slowly in $\approx 10-100$ seconds during such a burst. The typical energy emitted in a few seconds is $\sim 10^{39}$ ergs. These bursts are believed to originate from intermittent unstable nuclear burning of accreted matter accumulated on the neutron star surfaces, and hence are called thermonuclear bursts.

*email: sudip@tifr.res.in

The study of thermonuclear bursts provides a unique opportunity to understand some aspects of extreme physics. These bursts involve nuclear reactions and flow of matter in the strong gravity region, and hence they can be useful for testing laws of gravitation in strong gravity regime, and to study nuclear physics, fluid dynamics and plasma physics in extreme environments. The flow of matter during the burning involves convection and thermonuclear flame spreading (e.g., Spitkovsky et al. 2002; Bhattacharyya & Strohmayer 2005, 2006a,b,c, 2007a,c).

Thermonuclear bursts can also be useful for measuring neutron star parameters, and hence to constrain equation of state (EoS) models (Bhattacharyya 2010). For example, fitting of burst continuum spectrum with a blackbody model infers the emission area, and hence gives an estimate of the neutron star radius (van Paradijs 1979). However, this method of radius measurement has so far not been too successful because of systematic uncertainties (Bhattacharyya et al. 2010). Spectral line from a neutron star surface, which may be observed during bursts in the future, is affected by surface gravitational redshift, and hence can be used to measure the stellar radius-to-mass ratio. The shape of the line from a spinning neutron star can be useful for constraining other parameters too (Bhattacharyya et al. 2006a). Apart from the spectral properties of bursts, high frequency narrow timing features, viz. burst oscillations, have been detected from many thermonuclear X-ray bursts (e.g., Strohmayer & Bildsten 2006; Bhattacharyya 2007). The fitting of phase-folded burst oscillation lightcurves with an appropriate relativistic model can be useful for estimating source parameters, including neutron star radius-to-mass ratio (Bhattacharyya et al. 2005).

3. Broad relativistic iron line

A broad iron Kα spectral emission line near 6 keV is observed from many accreting supermassive and stellar-mass black hole systems (Reynolds & Nowak 2003, and references therein). This line is believed to originate from the inner part of the accretion disk, where an intrinsically narrow line is broadened and becomes asymmetric by Doppler and relativistic effects. The line is thought to be produced by the reflection of hard X-rays from the accretion disk. The hard X-ray source may be anything from an accretion disk corona (Fabian et al. 2000) to the base of a jet (Markoff & Nowak 2004). A given incident X-ray photon may be Compton scattered by free or bound electrons, or subject to photoelectric absorption followed by either Auger de-excitation or fluorescent line emission (Fabian et al. 2000). The strongest among the fluorescent spectral emission lines is the one for the $n = 2 \rightarrow n = 1$ transition of the iron atom (or ion). This iron Kα line originates at an energy between 6.4 keV and 6.97 keV, depending on the iron ionization state (Reynolds & Nowak 2003). The fitting of such a broad asymmetric line with appropriate models can be useful for measuring the black hole spin (Reynolds & Nowak 2003), as the spin affects the spacetime, and hence the shape of the line.

Bhattacharyya & Strohmayer (2007b), for the first time, established the inner accretion disk origin of the broad iron line from a neutron star LMXB, analyzing the

XMM-Newton data. Soon, Cackett et al. (2008) confirmed this finding using the independent *Suzaku* data from the same source. As of now, the inner disk origin of broad iron line has been confirmed for about ten neutron star LMXBs (e.g., Bhattacharyya & Strohmayer 2007b; Cackett et al. 2008; Pandel et al. 2008; Cackett et al. 2010; Miller et al. 2010). This opens up a new way to put an upper limit on the neutron star radius (Cackett et al. 2008), and to constrain the stellar EoS models (Bhattacharyya 2011). Since this line originates from the accretion flow in the strong gravity region, it can also be useful for testing the gravitational laws in strong field regime, and to study fluid dynamics and plasma physics in extreme environments.

4. Kilohertz quasi-periodic oscillation

High frequency quasi-periodic oscillations, or kilohertz (kHz) QPOs, often appear as a pair of peaks in the power spectra of some of the neutron star LMXBs, and the twin peaks usually move together in the frequency range $\sim 200-1200$ Hz in correlation with the source state (van der Klis 2006, and references therein). The higher frequency QPO is called the upper kHz QPO, and the lower frequency QPO is known as the lower kHz QPO. Although kHz QPOs are observationally robust features, their correct model is not yet known. However, the high frequency of these QPOs point towards the time scale of the strong gravity region within a few Schwarzschild radii of the neutron star. Naturally, according to many models, the kHz QPO frequencies are connected to the frequencies related to the fast motions close to a neutron star (e.g., Miller et al. 1998; Stella & Vietri 1998; Mukhopadhyay 2009). Here we identify some of these frequencies, and give expressions for them for circular orbits in the equatorial plane for Kerr spacetime.

(1) Orbital frequency around the neutron star $\nu_\phi = \nu_{\rm K}(1 + j(r_g/r)^{3/2})^{-1}$, where $\nu_{\rm K} = \sqrt{GM/r^3}/2\pi$. Here, r is the radial distance from the center of the neutron star, $r_g \equiv GM/c^2$, and the angular momentum parameter $j \equiv Jc/GM^2$, where J is the stellar angular momentum and M is the stellar mass.

(2) Radial epicyclic frequency (for infinitesimally eccentric orbits) $\nu_r = \nu_\phi(1-6(r_g/r)+8j(r_g/r)^{3/2} - 3j^2(r_g/r)^2)^{1/2}$.

(3) Vertical epicyclic frequency (for infinitesimally tilted orbits) $\nu_\theta = \nu_\phi(1-4j(r_g/r)^{3/2}+3j^2(r_g/r)^2)^{1/2}$.

(4) Periastron precession frequency $\nu_{\rm peri} = \nu_\phi - \nu_r$.

(5) Nodal precession frequency $\nu_{\rm nodal} = \nu_\phi - \nu_\theta$.

Apart from these, the neutron star spin frequency $\nu_{\rm spin}$ may also contribute to kHz QPOs. Since these frequencies involve neutron star parameters, as well as the effects of strong gravitational field, knowledge of the correct model of kHz QPOs will be very useful (1) for measuring neutron star parameters, (2) for testing laws of gravitation in strong field regime, and (3) for probing fluid dynamics and plasma physics in extreme conditions. In order to find the correct model, one needs to explain various properties of this feature, e.g., frequency, quality factor, rms amplitude, energy dependence, etc., as well as the modulation and decoherence mechanisms (e.g., van der Klis 2006; Méndez 2006; Barret et al. 2006; Mukherjee & Bhattacharyya 2011).

5. Conclusion

In this paper we have discussed how thermonuclear X-ray bursts, broad relativistic iron lines and kHz QPOs can be used to probe extreme aspects of neutron star LMXBs.

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