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Understanding high-density matter through analysis of surface spectral lines and burst oscillations from accreting neutron stars ☆

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Abstract

We discuss millisecond period brightness oscillations and surface atomic spectral lines observed during type I X-ray bursts from a neutron star in a low mass X-ray binary system. We show that modeling of these phenomena can constrain models of the dense cold matter at the cores of neutron stars. We demonstrate that, even for a broad and asymmetric spectral line, the stellar radius-to-mass ratio can be inferred to better than 5%. We also fit our theoretical models to the burst oscillation data of the low mass X-ray binary XTE J1814-338, and find that the 90% confidence lower limit of the neutron star's dimensionless radius-to-mass ratio is 4.2.

Keywords: Equation of state; Line: profiles; Relativity; Stars: neutron; X-rays: binaries; X-rays: bursts

1. Introduction

Understanding the properties of very high density ($\sim 10^{15}$ gm cm^{-3}, i.e., beyond nuclear density) cold matter at the cores of neutron stars is a fundamental problem of physics. Constraints on the proposed theoretical equation of state (EOS) models of such matter based on terrestrial experiments are difficult, because no experiments at such extreme densities at low temperature seem possible. The only way to address this problem is to measure the mass, the radius and the spin period of the same neutron star, as for a given EOS model and for a known stellar spin period, there exists a unique mass vs. radius relation for neutron stars. Any periodic variation in the observed lightcurve will provide us with the stellar spin period, if we can show that this periodic variation is due to stellar spin. But mass measurements usually require fortuitous observations of binaries, and radius estimates have historically been plagued with systematic uncertainties (see van Kerkwijk, 2004 for a recent summary of methods). Moreover, none of these methods can measure all three parameters of the same neutron star that are needed to constrain EOS models effectively.

We explore instead constraints based on the study of type I X-ray bursts from an accreting neutron star in an LMXB system. These bursts are convincingly explained as thermonuclear flashes on the stellar surface (Strohmayer and Bildsten, 2003, and references therein), and hence can give us information about the stellar parameters. In addition, the comparatively low magnetic field of a neutron star in an LMXB does not complicate the stellar emission of photons much (and hence keeps the modeling simple), which may not be the case for isolated neutron stars or neutron stars in other systems. The millisecond period brightness oscillations during type I

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X-ray bursts provide us with the stellar spin period, as this phenomenon is caused by the combination of stellar spin and an asymmetric brightness pattern on the stellar surface (Chakrabarty et al., 2003 and Strohmayer et al., 2003). During these X-ray bursts, atomic spectral lines may be observed from the stellar surface (as might be the case for the LMXB EXO 0748–676 and see Cottam et al., 2002). When properly identified, these lines provide the surface gravitational redshift value, and hence the stellar radius-to-mass ratio. The remaining stellar parameter can be obtained by detailed modeling of the structures of the burst oscillation lightcurves, and broadened & skewed (due to rapid stellar spin) surface atomic spectral lines. Here we calculate such theoretical models, and fit the burst oscillation models to the data of the LMXB XTE J1814-338 to constrain some stellar parameters.

2. Model computation

For the computation of burst oscillation lightcurves, we assume that the X-ray emitting region is a uniform circular hot spot on the stellar surface. In contrast, for our calculations of surface atomic spectral lines, we assume that the X-ray emitting portion is a belt that is symmetric around the stellar spin axis. This is because, for a typical spin frequency >10 Hz, any hot spot on the stellar surface will be effectively smeared into an axisymmetric belt during a typical integration time for spectral calculations. In both calculations, we consider the following physical effects (first four of these were considered by Özel and Psaltis, 2003): (1) Doppler shift due to stellar rotation, (2) special relativistic beaming, (3) gravitational redshift, (4) light-bending, and (5) frame-dragging. To include the effects of light-bending, we trace back the paths of the photons (numerically, in the Kerr spacetime) from the observer to the source using the method described in Bhattacharyya et al. (2001).

For a given EOS model, we have the following source parameters: two stellar structure parameters (radius-to-mass ratio and spin frequency), one binary parameter (observer's inclination angle), two emission region parameters (polar angle position and angular width of the belt or the hot spot), and a parameter n describing the emitted specific intensity distribution (in the corotating frame) of the form $I(\alpha) \propto \cos^n(\alpha)$, where α is the emission angle measured from surface normal. Other stellar structure parameters (mass and angular momentum) are found by computing the structure of the spinning neutron star, using the formalism given by Cook et al. (1994 and see also Bhattacharyya et al., 2000 and Bhattacharyya, Misra, and Thampan 2001).

3. Results and discussions

We have two main results: (1) if the stellar radius-to-mass ratio is inferred from the line centroid (which is the geometric mean of the low-energy and high-energy edges of the line profile), the corresponding error is in general less than 5% (Bhattacharyya et al., 2004), even when the observed surface line is broad and asymmetric. This is the accuracy needed for strong constraints on neutron star EOS models (Lattimer and Prakash, 2001). Other methods to infer this stellar parameter using surface lines (for example, using the peak energy of a line and see Özel and Psaltis, 2003) give much larger errors. (2) The 90% confidence lower limit of the dimensionless stellar radius-to-mass ratio of the LMXB XTE J1814-338 is 4.2 (see Bhattacharyya et al., 2005).

These results show that both surface spectral lines and burst oscillations can provide important information about the stellar parameters. These two phenomena were observed from the neutron star in the LMXB EXO 0748–676, and gave the values of stellar spin period (Villarreal and Strohmayer, 2004) and radius-to-mass ratio (Cottam et al., 2002). However, to measure the remaining stellar parameter (needed to constrain EOS models), we need larger instruments, partly due to the low duty cycle of bursts. But this at least indicates that these two surface spectral and timing features can originate from the same neutron star, and may help us constrain neutron star EOS models effectively, when observed with large area detectors of future generation X-ray missions, such as Constellation-X and XEUS.

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