Understanding High-Density Matter Through Analysis of Surface Spectral Lines and Burst Oscillations from Accreting Neutron Stars ⋆

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Abstract

We discuss the observed millisecond period brightness oscillations and surface atomic spectral lines during the type I X-ray bursts from a neutron star in a low mass X-ray binary system. We show that these help 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.

Key words: Equation of state, Line: profiles, Relativity, Stars: neutron, X-rays: binaries, X-rays: bursts

1 Introduction

Understanding the properties of very high density (beyond nuclear density; $\sim 10^{15}$ gm cm^{-3}) cold matter is a fundamental problem of physics. We are not

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certain about what kinds of particles exist at these densities or the nature of their interactions. Constraints based on terrestrial experiments are difficult, because no experiments at such extreme densities at low temperature seem possible. Fortunately, neutron stars act as natural laboratories for this kind of research, as the core density of a neutron star is several times that of nuclear density. To be more precise, if we can measure the mass, the radius and the spin period of the same neutron star, we will be able to constrain the high density equation of state of the core very effectively. This is because, for a given equation of state 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 has the potential to measure all three parameters of the same neutron star that are needed to constrain equation of state 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 (REFs), 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 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, 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; see Cottam, Paerels, & Méndez 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, as well as the surface atomic spectral lines. Due to stellar spin induced Doppler effects and special relativistic beaming, these lines will be broadened and skewed, and hence can be used to constrain stellar parameters.

Here we calculate theoretical models of burst oscillation lightcurves and fit our models to the data of the LMXB XTE J1814-338 to constrain some stellar parameters. We compute models of surface atomic spectral lines and show that even for a very broad and asymmetric spectral line, stellar radius-to-mass ratio can be inferred to better than 5%.

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, during a typical spin frequency > 10 Hz, any hot spot on the stellar surface will be effectively smeared into an axisymmetric belt. In both calculations, we consider the following physical effects: (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, Bhattacharya, & Thampan (2001). [MUST CITE OZEL AND PSALTIS HERE]

For a given equation of state 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 specific angular momentum) are found by computing the structure of the spinning neutron star, using the formalism given by Cook, Shapiro, & Teukolsky (1994; see also Bhattacharyya et al. 2000, Bhattacharyya, Misra, & Thampan 2001).

3 Results and Discussions

We have two main results:

1) Although for a broad and asymmetric observed line, the surface gravitational redshift (and hence the radius-to mass ratio) measured from the energy of the deepest minimum (or, highest maximum for emission lines), or from the arithmetic mean of the low-energy and high-energy edges of the observed line, has a large error, the error in the stellar radius-to-mass ratio computed from the line centroid using the geometric mean of the low-energy and high-energy edges of the observed line is in general less than 5% (Bhattacharyya, Miller, &

Lamb 2004). This is the accuracy needed for strong constraints on neutron star equation of state models (REF). [MENTION OZEL AND PSALTIS WORK]

2) The 90% confidence lower limit of the dimensionless stellar radius-to-mass ratio of the LMXB XTE J1814-338 is 4.2 (Bhattacharyya et al. 2005).

These results show that both surface spectral line and burst oscillation can give 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 and radius-to-mass ratio. However, due to the poor quality data [WHAT DO YOU MEAN? DID THE OBSERVERS DO A BAD JOB?], the remaining stellar parameter (needed to constrain equation of state models) could not be measured. But this at least indicates that these two surface spectral and timing features can be originated from the same neutron star, and by the observations with large area detectors of future generation X-ray missions (such as Constellation-X or XEUS), they may help us constrain neutron star equation of state models effectively.

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