

Surface Atomic Spectral Lines from Weakly Magnetic Rotating Neutron Stars

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Abstract. The profiles of atomic spectral lines from the surfaces of neutron stars can provide important information about stellar structure and the emission geometry, which in turn may help constrain models of the high density cold matter in the cores of neutron stars. An observed surface line will be affected by several physical effects, such as Doppler shifts (due to stellar rotation), special relativistic beaming, gravitational redshifts, light-bending, and frame-dragging. We have computed theoretical models for such lines, taking all these effects into account in the context of weakly magnetized, rapidly rotating neutron stars in low-mass X-ray binaries. We find that the stellar radius-to-mass ratio can be inferred from surface line profiles to better than 5%, even for a broad and asymmetric observed line. Our results also indicate that a signature of frame-dragging may be detected from future detailed studies of the shapes of surface atomic lines.

INTRODUCTION

The recent report (Cottam, Paerels, & Méndez 2002) of atomic resonant scattering lines from the surface of the neutron star in the low mass X-ray binary (LMXB) EXO 0748–676 has stimulated new work on the physics of surface spectral lines from neutron stars (see, for example, Özel & Psaltis 2003; Loeb 2003; Bildsten, Paerels, & Chang 2003; Villarreal & Strohmayer 2004). This is because the identification of such a line provides the gravitational redshift at the neutron star surface, and hence the stellar radius-to-mass ratio, a key parameter that constrains the equation of state of dense cold matter.

Cottam et al. (2002) detected three surface lines (Fe XXV $H\alpha$, Fe XXV 2–3, and possibly O VIII $Ly\alpha$) using the burst data from XMM-Newton. The corresponding surface gravitational redshift value for all three lines is ~ 0.35 , which gives a dimensionless stellar radius-to-mass ratio (R/M) of 4.4. The narrowness of the observed iron lines is consistent with the slow rotation rate of the neutron star (spin frequency ~ 45 Hz; Villarreal & Strohmayer 2004), but such a narrow line provides information only about R/M , and does not help us constrain other system parameters. Therefore, while the slow stellar rotation for this particular source was an important reason behind the detection of these lines with XMM-Newton (because the rotational Doppler broadening was small, and hence the depth of the line was large enough for detection), it will be difficult to constrain other system parameters by future observation of surface lines from this source with better instruments. However, as the typical spin frequency of an accreting neutron star in an LMXB is 200 – 600 Hz (Lamb & Yu 2004), the rotational Doppler broadening of the observed line may enable us to study the detailed shape of the line, and hence

constrain several system parameters. Therefore, future observation of such broad lines by larger area detectors may be able to determine more than one stellar structure parameter with enough precision to obtain tight constraints on models of the equation of state of dense matter.

We have computed theoretical models of observed line profiles, using realistic neutron star equation of state models, and considering the effects of stellar spin and special and general relativity on the lines. We demonstrate that it is possible to determine the stellar surface gravitational redshift value (and hence R/M) with high precision, even if the observed line is broad and asymmetric. We also show that the properties of the two expected flux minima in a line may be used to detect frame-dragging.

MODEL COMPUTATION

We assume the X-ray emitting portion of the surface to be a belt that is symmetric around the spin axis of the neutron star. This is justified, because during a typical integration time (order of seconds) for spectroscopic measurements, and for a stellar spin frequency > 10 Hz, any hot spot on the stellar surface will be effectively smeared into an axisymmetric belt. In our calculation, we consider the following physical effects on the observed line profile structure: (1) Doppler shift due to stellar rotation, (2) special relativistic beaming, (3) gravitational redshift, (4) light-bending, and (5) frame-dragging (Özel & Psaltis 2003 considered the first four of these effects). 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, Bhattacharyya, & Thampan (2001).

For a given neutron star matter equation of state, we have several source parameters. These are two stellar structure parameters (radius-to-mass ratio and spin frequency), one binary parameter (observer's inclination angle), two emitting-belt parameters (polar angle position and angular width of the belt), 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. To find the values of other stellar structure parameters (mass and specific angular momentum) required for line profile calculations, we compute (for a given equation of state model) the structure of the rotating neutron star, using the formalism given by Cook, Shapiro, & Teukolsky (1994; see also Bhattacharyya et al. 2000, Bhattacharyya 2002).

RESULTS AND DISCUSSIONS

We obtain two main results (Bhattacharyya, Miller, & Lamb 2004):

- 1) If the observed line profile is broad and asymmetric, the surface gravitational redshift measured from the energy of the deepest minimum (or, highest maximum for emission lines) will typically have a large error (Özel & Psaltis 2003). Even if we use the centroid energy of the line profile obtained from the arithmetic mean of the low-energy and high-energy edges of the observed line, the fractional error in the inferred redshift value, and hence in the stellar R/M , will typically be large. We find, however, that if we

calculate the line centroid using the geometric mean of the low-energy and high-energy edges of the observed line, the percentage error in the inferred R/M value 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.

2) We find that the ratio of the flux deficit in the low-energy minimum to that in the high-energy minimum is increased by frame-dragging. This ratio, therefore, contains an observable signature of frame-dragging (Bhattacharyya, Miller, & Lamb 2004).

In a more detailed study we will relate the observable line profile parameters (such as line width, ratio of flux deficits in the flux minima, etc.) to the full set of source parameters. Future observations of surface spectral lines with larger detector area instruments in proposed X-ray space missions (e.g., Constellation-X) will help constrain stellar parameters, and will provide a way to detect frame-dragging.

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