Ways to constrain neutron star equation of state models using relativistic disc lines

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ABSTRACT

Relativistic spectral lines from the accretion disc of a neutron star low-mass X-ray binary can be modelled to infer the disc inner edge radius. A small value of this radius tentatively implies that the disc terminates either at the neutron star hard surface, or at the innermost stable circular orbit (ISCO). Therefore an inferred disc inner edge radius either provides the stellar radius, or can directly constrain stellar equation of state (EoS) models using the theoretically computed ISCO radius for the space–time of a rapidly spinning neutron star. However, this procedure requires numerical computation of stellar and ISCO radii for various EoS models and neutron star configurations using an appropriate rapidly spinning stellar space–time. We have fully general relativistically calculated about 16 000 stable neutron star structures to explore and establish the above mentioned procedure, and to show that the Kerr space–time is inadequate for this purpose. Our work systematically studies the methods to constrain EoS models using relativistic disc lines, and will motivate future X-ray astronomy instruments.

Key words: accretion, accretion discs – equation of state – methods: numerical – stars: neutron – X-rays: binaries.

1 INTRODUCTION

The core density of a neutron star is typically 5–10 times higher than the nuclear density. Such a dense matter at a relatively low temperature (e.g. \( \sim 10^8 \) K) cannot be probed by heavy-nuclei collision experiments or with observations of the early universe (Lattimer & Prakash 2007 and references therein). Plausibly the only way to probe this degenerate matter is to constrain the theoretically proposed equation of state (EoS) models of neutron star cores (Shapiro & Teukolsky 1983). For a given EoS model and an assumed central density, the stable structure of a non-spinning neutron star can be computed by solving the Tolman–Oppenheimer–Volkoff (TOV) equation (Shapiro & Teukolsky 1983). These stable stars trace a single curve in the mass \((M)\)–equatorial radius \((R)\) space. Therefore, measurement of mass and radius of the same non-spinning neutron star would constrain the EoS models. If the neutron star spins, then the EoS models can be constrained by the reliable measurements of three independent parameters, such as mass, radius and spin-frequency \((\nu_{\text{spin}})\) of the same neutron star (e.g. fig. 1 of Bhattacharyya 2010). This is extremely difficult because of a number of unknown systematics. Low-mass X-ray binaries (LMXBs) can be particularly promising systems for such measurements, because several complementary methods are available for them. A recent review by Bhattacharyya (2010) describes how the simultaneous application of these methods can reduce the systematic uncertainties.

One such method involves broad relativistic spectral lines from the inner portion of the accretion disc. The strongest among these fluorescent spectral emission lines is the one for the \( n = 2 \rightarrow n = 1 \) transition of the iron atom (or ion), and is observed from many accreting supermassive and stellar-mass black hole systems (see Reynolds & Nowak 2003; Miller 2007, and references therein). Recently, Bhattacharyya & Strohmayer (2007) has, for the first time, established that the broad iron lines from neutron star LMXBs also originate from the inner accretion discs. This discovery was soon confirmed by Cackett et al. (2008) using data from a different satellite. After these initial reports, the inner disc origin of broad iron line has been confirmed for several other neutron star LMXBs (e.g. Pandel, Kaaret & Corbel 2008; Cackett et al. 2009, 2010; D’Aì et al. 2009; di Salvo et al. 2009; Iaria et al. 2009; Papitto et al. 2009; Reis, Fabian & Young 2009).

The broad iron line is affected by the strong gravity and spin of the compact star (neutron star or black hole). Before discussing how this relativistic line can be used to constrain the neutron star parameters, let us see how it infers the black hole spin. The line shape, especially the extent of the red wing, carries the signature of the disc inner edge radius in the unit of stellar mass \((r_{\text{in}}c^2/GM)\). This is because the red wing is primarily affected by longitudinal Doppler effect due to the orbital motion of the disc matter, which broadens the line, and gravitational redshift, which shifts the line towards lower energies. Since, for a black hole the disc can extend...
up to the innermost stable circular orbit (ISCO), the black hole spin parameter $j = Jc/GM^2$ ($J$: total angular momentum; $M$: mass), which determines the ISCO location, can be estimated by fitting the line shape with an appropriate relativistic model for Kerr space–time (Lar 1991; Beckwith & Done 2004; Dovčiak, Karas & Yaqoob 2004; Miller 2007).

A neutron star system is usually more complex than a black hole system because of the following reasons. (1) While a spinning black hole is defined by only two parameters (mass and spin), and the space–time around it is the Kerr space–time having analytical expressions, the structures and space–times of rapidly spinning neutron stars, usually harboured by LMXBs, may have to be numerically calculated from at least two parameters apart from the EoS model (Cook, Shapiro & Teukolsky 1994). (2) Unlike a black hole, a neutron star has a hard surface which can have observable effects. Therefore, for a neutron star, the disc may be terminated either by ISCO or by the stellar surface (Thampan, Bhattacharya & Datta 1999). An example of the competition between these two effects has been shown in the fig. 1 of Miller, Lamb & Cook (1998) and fig. 1 of Bhattacharyya et al. (2000), which demonstrate that usually circumferential radius $r_m$ of disc inner edge first decreases and then increases with the increase of stellar spin for a given EoS model and mass. This complicates the measurement of $Jc/GM^2$ and other stellar parameters using the inferred circumferential $r_m c^2/GM$, if it is not known whether the disc terminates at ISCO or at the stellar surface. Therefore, theoretical computations of $r_m$ as a function of stellar parameters for various EoS models are essential. Such computations will also be useful to determine if a measured $r_m c^2/GM$ directly gives the neutron star radius to mass ratio $Rc^2/GM$. Note that the computations of $r_m$ and stellar parameters will involve the numerical calculations of rapidly spinning neutron star structures, and hence Kerr space–time cannot be used. Moreover, in order to constrain the EoS models, directly measurable neutron star parameters (e.g. $Rc^2/GM$, $M$, $v_{\text{spin}}$, see Bhattacharyya 2010) should be expressed as functions of $r_m c^2/GM$. Since $Jc/GM^2$ cannot usually be measured directly, a $Jc/GM^2$ versus $r_m c^2/GM$ plot may not be very useful to constrain the EoS models. In this paper, such plots (Figs 1, 2 and 3) have been shown for comparisons with Kerr space–time and to gain insight (Section 3).

Figure 1. Neutron star angular momentum parameter ($Jc/GM^2$) versus disc inner edge radius to stellar mass ratio ($r_m c^2/GM$). The solid curve is for Kerr space–time (Section 1). Various symbols give the curves for different neutron star EoS models (Section 2) for $M = 1.4M_\odot$ and $v_{\text{spin}}$ ranging from 0 to 750 Hz. The negative slope of the curves implies that the disc terminates at ISCO, while the positive slope implies that it terminates at the stellar surface. This figure shows that the realistic $r_m c^2/GM$ values for neutron stars can significantly deviate from the Kerr values.

The procedure of constraining EoS models using directly measurable parameters versus $r_m c^2/GM$ relations can be utilized only if $r_m c^2/GM \lesssim 6$, because a much larger value of $r_m c^2/GM$ might imply the truncation of the disc by other effects (see Section 4). Particularly useful would be $r_m c^2/GM < 6$, because such values will confirm the effect of neutron star spin on a corotating disc. Therefore, a crucial question is whether observations show that $r_m c^2/GM \lesssim 6$. Cackett et al. (2010) report that $r_m c^2/GM$ values fall into a small range of 6–15 for most of the neutron star LMXBs with established relativistic disc lines. Moreover, although these authors could not measure a value of $r_m c^2/GM$ less than 6 (as they used non-spinning, i.e. Schwarzschild space–time), many of their fitted $r_m c^2/GM$ values across the sources pegged at the lower limit 6. This happened for both phenomenological and reflection models, and even when the Compton broadening was taken into account (Cackett et al. 2010). Such pegged best-fitting values strongly suggest that $r_m c^2/GM < 6$ for many cases, which is supported by the disc line fitting with spinning Kerr space–time models (Bhattacharyya & Strohmayer 2007; Papitto et al. 2009; Reis et al. 2009; D’Ai et al. 2010). This provides a good motivation to theoretically explore the above mentioned procedure to constrain the EoS models.

Since, in this paper, we have computed neutron star structures and the corresponding ISCO locations, let us briefly review some of the...
previous studies on this topic. Kluzniak & Wagoner (1985) computed ISCO location with slow stellar spin approximation. Cook et al. (1994) numerically calculated rapidly spinning neutron star structures in full general relativity using realistic EoS models. Miller et al. (1998) used these structure calculations to compute ISCO locations for a few cases. Stergioulas, Kluzniak & Bulik (1999) studied if strange stars in LMXBs could be excluded using the orbital frequency at ISCO. The relevance of higher order multipoles on the ISCO location was analytically probed by Shibata & Sasaki (1998). Berti & Stergioulas (2004) computed stellar models, multipole moments and ISCO locations, and compared the ISCO results with the Manko, Mielke & Sanabria-Gómez (2000a) and Manko, Sanabria-Gómez & Manko (2000b) results for analytic solution for space–time around rapidly spinning neutron stars, Kerr ISCO results and Shibata & Sasaki (1998) results. The results of Berti & Stergioulas (2004) show that higher multipole moments cause differences between rapidly spinning neutron star ISCO and Kerr ISCO. Pachon, Rueda & Sanabria-Gómez (2006) and Sanabria-Gomez et al. (2010) studied the ISCO around a spinning magnetic neutron star. Abramowicz et al. (2003) calculated circular geodesics in the Hartle–Thorne metric for slowly spinning neutron stars. Berti et al. (2005) found that Hartle–Thorne approximation gives ISCO radii accurate to within 1 per cent. Bejger, Zdunik & Haensel (2010) suggested approximate analytic expressions for circular orbits around rapidly spinning neutron stars.

Disc lines have so far been used to measure the black hole spin (e.g. Brenneman & Reynolds 2006). It has also been proposed that these lines could be used to put an upper limit on the neutron star radius (Bhattacharyya & Strohmayer 2007; Cackett et al. 2008) and to constrain other stellar parameters (Bhattacharyya 2010). However, to the best of our knowledge, plausible methods to measure these parameters, and hence to constrain the EoS models in a systematic way using appropriate space–times have not been studied so far. The aim of this paper is to explore these methods. We have done so by calculating a huge number of neutron star structures, and the corresponding ISCO locations, if such a location is outside the neutron star. Although, a large set of papers reported the studies on such structures and locations (as indicated in the previous paragraph), none of these aimed to probe neutron star parameters using iron lines. In Sections 2, 3 and 4, we describe our method, give the results and provide a discussion respectively. Note that, since the accretion disc is believed to be thin, we have not considered non-equatorial orbits in our calculations. We have also not considered counterrotating orbits, because that would imply $r_{\rm ISCO}/GM > 6$, which could be easily confused with truncations caused by other effects (see Section 4).

2 METHOD

In this section, we briefly describe the procedure to compute rapidly spinning neutron star structures, and their equilibrium sequences. The space–time around such a star can be described by the following metric (using $c = G = 1$; Bardeen 1970; Cook et al. 1994):

$$
\text{d}r^2 = -e^{\gamma + \rho} \text{d}t^2 + e^{\rho} (\text{d}r^2 + r^2 \text{d}\theta^2) + e^{\gamma - \rho} r^2 \sin^2 \theta (\text{d}\phi - \omega \text{d}t)^2,
$$

where the metric potentials $\gamma$, $\rho$, $\alpha$ and the angular speed ($\omega$) of the stellar fluid relative to the local inertial frame are all functions of $r$ and $\theta$. For a given EoS model, and assumed values of stellar central density and polar-radius to equatorial-radius ratio, Einstein’s field equations can be solved to find out $r$ and $\theta$ dependence of $\gamma$, $\rho$, $\alpha$ and $\omega$, as well as to obtain the stable stellar structure.

(1)

(Cook, Shapiro & Teukolsky 1994; Datta, Thampan & Bombaci 1998; Bhattacharyya et al. 2000, 2001a,b,c; Bhattacharyya 2002). So far Kerr space–time has been used to model the iron lines from spinning neutron star systems. Therefore, first we examine how our $Jc/\sqrt{GM^2}$ versus $r_{\rm ISCO}/GM$ plot deviates from the corresponding Kerr curve, in order to find out if Kerr calculations for iron lines can give acceptable constraints on neutron star parameters. Fig. 1 shows when the equatorial radius of the neutron star is smaller than the

3 RESULTS

We have computed $v_{\rm spin}$ sequences (Section 2) for 15 $v_{\rm spin}$ values in the range of 0–750 Hz for each EoS model. About 16000 neutron star structures have been calculated to establish our results, and we give example figures in this section using a fraction of our computed numbers. The code to compute these structures and $r_{\rm ISCO}$ values is well tested (Datta et al. 1998; Thampan & Datta 1998; Bhattacharyya et al. 2000, 2001a,b,c; Bhattacharyya 2002). So far Kerr space–time has been used to model the iron lines from spinning neutron star systems. Therefore, first we examine how our $Jc/\sqrt{GM^2}$ versus $r_{\rm ISCO}/GM$ plot deviates from the corresponding Kerr curve, in order to find out if Kerr calculations for iron lines can give acceptable constraints on neutron star parameters. Fig. 1 shows when the equatorial radius of the neutron star is smaller than the
ISCO radius, the deviation is relatively small, but is not negligible, depending on the values of $v_{\text{spin}}$ and $M$ and the chosen EoS model. But when the neutron star equatorial radius is larger than the ISCO radius (see, for example, Miller et al. 1998), the deviation is large because stellar equatorial radius increases with the increase of $v_{\text{spin}}$, and such a situation does not occur for black holes (Kerr space–time). For example, for the EoS model A, the stellar equatorial radius is greater than the ISCO radius for all $v_{\text{spin}}$ values for $M = 1.4M_{\odot}$, and hence the deviation is always very large. However, for $M = 2.0M_{\odot}$, the stellar equatorial radius is less than the ISCO radius for smaller values of $v_{\text{spin}}$ (Fig. 2). In this case, the curves for both EoS models A and B are closer to the Kerr curve compared to these curves for $M = 1.4M_{\odot}$. However, for $M = 2.0M_{\odot}$, stable neutron star structures do not exist for EoS models C and D. Therefore, from Figs 1 and 2 we find that the deviation is more for (1) higher $v_{\text{spin}}$, (2) lower $M$ and (3) stiffer EoS models. The first two effects can also be seen in fig. 1 of Miller et al. (1998). These effects are expected for $r_{\text{ms}}c^2/GM = Rc^2/GM$, because all these three points result in the increase of $R$. Let us now try to understand these points for $r_{\text{ms}}c^2/GM = r_{\text{ISCO}}c^2/GM$. The first point is understandable, because for $v_{\text{spin}} = 0$ the space–time outside even a neutron star is Schwarzschild, which is the non-spinning special case of Kerr. The second point could be understood from the fact that for lower $M$ the neutron star is usually less compact (that is the hard surface is farther from the centre), causing its space–time to deviate more from that of a black hole. The third point may be explained from the lesser stellar compactness for a stiffer EoS model for given $M$ and $v_{\text{spin}}$. However, we find that if $M/M_{\text{max}}$ is kept fixed instead of $M$, the differences among the $Jc^2/GM^2$ versus $r_{\text{ms}}c^2/GM$ curves for various EoS models are small (Fig. 3). This indicates that $M_{\text{max}}$ may be a suitable parameter to characterize an EoS model.

After finding that the Kerr space–time is usually not good enough to model $r_{\text{ms}}c^2/GM$, and since this space–time cannot be used for neutron star parameter calculation, we have explored ways to constrain stellar EoS models using appropriate general relativistic computations for neutron stars (see Section 2). We have checked the relation between $r_{\text{ms}}c^2/GM$ and a few stellar parameters, which can be measured from independent methods. These parameters are $v_{\text{spin}}$, $Rc^2/GM$ and $M$. Whenever $v_{\text{spin}}$ can be measured (using regular pulsations or burst oscillations; Bhattacharyya 2010), it is measured very accurately. Therefore, in the Figs 4, 5, 6 and 7, we have fixed $v_{\text{spin}}$, $Rc^2/GM$ and $M$, on the other hand, may be constrained in a range (using thermonuclear X-ray bursts, binary orbital motions, etc.; Bhattacharyya 2010), and hence we have used them as dependent variables in these figures. Figs 4 and 5 show $Rc^2/GM$ versus $r_{\text{ms}}c^2/GM$ plots for two values of $v_{\text{spin}}$ and four EoS models. For a given $v_{\text{spin}}$ value, and if the stellar equatorial radius is less than the ISCO radius, each EoS model traces a distinct curve. These curves, which are more separated from each other for higher $v_{\text{spin}}$, can be used to constrain EoS models from the $r_{\text{ms}}c^2/GM$ value inferred from the iron line fitting, and the $Rc^2/GM$ value measured independently (see Bhattacharyya 2010). These figures show that even if $Rc^2/GM$ is not well constrained, a suitable upper limit of $r_{\text{ms}}c^2/GM$ can reject softer EoS models. If the stellar equatorial radius is larger than the ISCO radius, an oblique straight line is found for all EoS models, and an inferred $r_{\text{ms}}c^2/GM$ value directly gives the $Rc^2/GM$ value. Figs 4 and 5 clearly show the value of $r_{\text{ms}}c^2/GM$ (for a given $v_{\text{spin}}$), above which $r_{\text{ms}}c^2/GM$ can be used to directly infer the EoS-model-independent $Rc^2/GM$ value. Figs 6 and 7 show even if, instead of $Rc^2/GM$, $M$ is known from independent measurement (Bhattacharyya 2010), $r_{\text{ms}}c^2/GM$ inferred from iron line can be used to constrain the EoS models. Even for an unknown $M$, a suitable upper limit of $r_{\text{ms}}c^2/GM$ can be used to reject softer EoS models.

![Figure 4. Neutron star equatorial radius to mass ratio ($Rc^2/GM$) versus disc inner edge radius to stellar mass ratio ($r_{\text{ms}}c^2/GM$) for various EoS models (Section 2) for $v_{\text{spin}} = 200$ Hz. Note that the oblique straight line portions of the curves are for $r_{\text{ms}}c^2/GM = Rc^2/GM$. This figure shows how a $r_{\text{ms}}c^2/GM$ value inferred from iron line can be used to constrain the EoS models for a known $v_{\text{spin}}$ value (Section 3).](image1)

![Figure 5. Neutron star equatorial radius to mass ratio ($Rc^2/GM$) versus disc inner edge radius to stellar mass ratio ($r_{\text{ms}}c^2/GM$) for various EoS models (Section 2) for $v_{\text{spin}} = 600$ Hz (similar to Fig. 4).](image2)

![Figure 6. Neutron star mass ($M$) versus disc inner edge radius to stellar mass ratio ($r_{\text{ms}}c^2/GM$) for various EoS models (Section 2) for $v_{\text{spin}} = 200$ Hz. Note that the oblique straight line portions of the curves are for $r_{\text{ms}}c^2/GM = Rc^2/GM$. This figure shows how a $r_{\text{ms}}c^2/GM$ value inferred from iron line can be used to constrain the EoS models for a known $v_{\text{spin}}$ value (Section 3).](image3)
to constrain EoS models. Similar result is shown in Fig. 9, where $\frac{Rc^2}{GM}$ is known and $M$ is reasonably constrained. However, for these two procedures (Figs 8 and 9), measurements of $\frac{Rc^2}{GM}$ and $M$ appear to be more important than an inferred $r_{in}c^2/ GM$.

*Figure 7.* Neutron star mass ($M$) versus disc inner edge radius to stellar mass ratio ($r_{in}c^2/ GM$) for various EoS models (Section 2) for $v_{spin} = 600$ Hz (similar to Fig. 6).

*Figure 8.* Neutron star equatorial radius to mass ratio ($Rc^2/ GM$) versus disc inner edge radius to stellar mass ratio ($r_{in}c^2/ GM$) for various EoS models (Section 2) for $M = 1.4 M_\odot$. Note that the oblique straight line portions of the curves are for $r_{in}c^2/ GM = Rc^2/ GM$. This figure shows, for a known $M$, how a $r_{in}c^2/ GM$ value inferred from iron line can be used to constrain the EoS models (Section 3).

*Figure 9.* Neutron star mass ($M$) versus disc inner edge radius to stellar mass ratio ($r_{in}c^2/ GM$) for various EoS models (Section 2) for $Rc^2/ GM = 4.0$. This figure shows, for a known $Rc^2/ GM$, how a $r_{in}c^2/ GM$ value inferred from iron line can be used to constrain the EoS models (Section 3).

4 DISCUSSION

In this paper, we explore ways to constrain neutron star EoS models by comparing the inferred values of $r_{in}c^2/ GM$ with the theoretical values. A $r_{in}c^2/ GM$ value may be inferred by fitting the relativistic disc lines with appropriate models (Bhattacharyya 2010). We have shown that $r_{in}c^2/ GM$ calculated from Kerr space–time is inadequate to distinguish between EoS models even when $r_{in}c^2/ GM = R_{ISCO}c^2/ GM$, and can largely differ from the correct value for rapidly spinning neutron star space–time when $r_{in}c^2/ GM = Rc^2/ GM$. We have numerically computed a huge number of $r_{in}c^2/ GM$ values, assuming that the disc terminates either at ISCO or at the stellar hard surface. This should be at least approximately true for $r_{in}c^2/ GM \lesssim 6$, although systematics may be introduced due to the effects of magnetic field and radiative pressure. Such systematics would imply that any inferred $r_{in}c^2/ GM$ value is basically an upper limit of $r_{ISCO}c^2/ GM$ or $Rc^2/ GM$, which can still be used to reject softer EoS models (Figs 4, 5, 6 and 7). These systematics can be reduced by detailed modelling of these effects, as well as by independent observations. We have studied the relations between $r_{in}c^2/ GM$ and several directly measurable neutron star parameters (Bhattacharyya 2010), in order to establish new ways to constrain EoS models. We have found that this iron line method could be effective to constrain EoS models, if the neutron star spin frequency is independently measured (Bhattacharyya 2010). This work is timely and important, as it provides motivation for future X-ray missions, and because of the rapid progress in the disc line field via observations with XMM–Newton, Suzaku and Chandra.

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