

Constraining the neutron star equation of state using XMM-Newton

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We have identified three possible ways in which future XMM-Newton observations can provide significant constraints on the equation of state of neutron stars. First, using a long observation of the neutron star X-ray transient Cen X-4 in quiescence one can use the RGS spectrum to constrain the interstellar extinction to the source. This removes this parameter from the X-ray spectral fitting of the pn and MOS spectra and allows us to investigate whether the variability observed in the quiescent X-ray spectrum of this source is due to variations in the soft thermal spectral component or variations in the power law spectral component coupled with variations in N_{H} . This will test whether the soft thermal spectral component can indeed be due to the hot thermal glow of the neutron star. Potentially such an observation could also reveal redshifted spectral lines from the neutron star surface. Second, XMM-Newton observations of radius expansion type I X-ray bursts might reveal redshifted absorption lines from the surface of the neutron star. Third, XMM-Newton observations of eclipsing quiescent low-mass X-ray binaries provide the eclipse duration. With this the system inclination can be determined accurately. The inclination determined from the X-ray eclipse duration in quiescence, the rotational velocity of the companion star and the semi-amplitude of the radial velocity curve determined through optical spectroscopy, yield the neutron star mass.

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1 Introduction

Low-mass X-ray binaries are binary systems in which a $\lesssim 1M_{\odot}$ star transfers matter to a neutron star or a black hole. A large fraction of the low-mass X-ray binaries is found to be transient – the so called soft X-ray transients (here, we will just refer to them as X-ray transients, see e.g. Chen, Shrader & Livio 1997). Before the arrival of the XMM-Newton and Chandra satellites only a few neutron star X-ray transients could be studied in quiescence (e.g. the system Cen X-4 and Aql X-1, Van Paradijs et al. 1987; McClintock, Horne & Remillard 1995; Campana et al. 1997). Using the XMM-Newton and Chandra satellites many more systems have been studied in quiescence (see e.g. Rutledge et al. 2001; Wijnands et al. 2001, 2002; Campana et al. 2003; Jonker et al. 2003; Tomsick et al. 2004; Heinke et al. 2007 to name but a few references) and Cen X-4 and Aql X-1 were studied in much more detail than was possible before (e.g. Campana et al. 2004; Rutledge et al. 2002). As we will explain below, these observations can have a profound impact on an important area of astrophysics: determining the neutron star equation of state (EoS). This is one of the ultimate goals of the study of neutron stars.

Recent theoretical progress provides the framework for the interpretation of X-ray observations of quiescent low-mass X-ray binaries (e.g. Brown, Bildsten & Rutledge 1998;

Colpi et al. 2001; Zavlin, Pavlov & Shibakov 1996; Gaensicke, Braje & Romani 2002; Heinke et al. 2006). Theoretically, one expects the neutron star to emit X-rays even after accretion has stopped. This emission can be modelled by a neutron star atmosphere (NSA) model. The NSA models have four free parameters. The neutron star distance, mass, radius and temperature. Due to the large heat capacity the temperature of the neutron star core is set on timescales of tens of thousands of years (Colpi et al. 2001) and depends on the equilibrium between the heating and the cooling rate of the neutron star. The heating rate depends on the total amount of accreted baryons and the pycnonuclear reactions taking place a few hundred meters deep in the crust (Haensel & Zdunik 1990; Brown, Bildsten & Rutledge 1998; Colpi et al. 2001). The time-averaged mass accretion rate in neutron star transients can be derived from binary evolution models if the orbital period is known (Kraft, Mathews & Greenstein 1962). The pycnonuclear reactions taking place in the neutron star crust are described in Salpeter & Van Horn (1969) and Kitamura (2000). The balance between the heating and cooling rates sets the neutron star core temperature (for a review of the cooling properties see e.g. Yakovlev & Pethick 2004). In theory, a NSA-fit provides means to measure the mass and radius of the neutron star and thus constrain the equation of state (EoS) of matter at supranuclear densities.

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In practice, spectra of neutron star transients in quiescence where the flux is high enough to allow for a spectral study, can indeed be well-fit by a neutron star atmosphere model (NSA). Sometimes, additional emission is present at energies above a few keV, often quantified by a power-law. When systems are selected for which the distance is well known (e.g. sources in globular clusters), neutron star masses and radii can be determined accurately. Canonical neutron star values were found (e.g. Heinke et al. 2003; Webb & Barret 2007), rendering support for the interpretation that the soft X-ray spectral component is due to the NSA. Besides fitting for the neutron star radius and mass in the NSA modelling, there is another way to derive a constraint on the neutron star mass. Namely, by investigating the neutron star temperature. The stringent upper limit on the NSA spectral component to the luminosity of SAX J1808.4–3658 ($\lesssim 10\%$; Campana et al. 2002; Heinke et al. 2007) and the stringent limit on the luminosity and thus neutron star temperature in 1H 1905+000 (Jonker et al. 2006, 2007) hint at massive neutron stars in these two transients. The reasoning behind this is the following: the upper limit on the thermal spectral component implies low core temperatures, which implies a rapid release via enhanced neutrino emission of the energy produced in the crust. This enhanced neutrino emission can only occur if the neutron star mass is larger than $1.6\text{--}1.7 M_{\odot}$ (Yakovlev & Pethick 2004). Neutron stars with masses well above $1.4 M_{\odot}$ cannot exist for so-called soft equations of state (EoS), in which matter at high densities is relatively compressible (e.g., due to a meson condensate or a transition between the hadron and quark-gluon phases). An important caveat is that the heating accretion history of the last several tens of thousands of years has to be determined from binary evolution models.

In this manuscript we identify three possible ways in which future XMM-Newton observations can provide constraints on the neutron star EoS.

2 Usage of the XMM-Newton RGS spectra

Even though Heinke et al. (2003) and Webb & Barret (2007) find values for the neutron star mass and radius consistent with those of canonical neutron stars, it is still not certain whether the soft thermal spectral component is really due to the cooling neutron star. Substantial variations in the quiescent X-ray luminosity of Aql X-1 and Cen X-4 have been observed (cf. Campana et al. 1997; Rutledge et al. 2002; Campana et al. 2003). The question is: is this variability caused by variations in the soft spectral component or by (coupled) variability in N_{H} and the power-law? Currently, the favoured explanation is that the power-law spectral component varies in accord with N_{H} (Campana et al. 2003, 2004). In this way the thermal spectral component can be kept constant. Alternatively, if the soft thermal component varies on short time scales there is a problem with the interpretation that it arises from the NSA. The neutron star mass, radius, distance and temperature cannot vary on

short timescales. This said, it turns out that small observed changes in the neutron star effective temperature can be explained in light of a NSA model if an outburst or a type I X-ray burst took place between the observations that provide the evidence for variability. Namely, small temperature changes can be caused by changes in the heat blanketing layer below the neutron star atmosphere (Brown, Bildsten & Chang 2002). The heat blanketing layer consists of ashes of nuclear burning produced in type I X-ray bursts and of a layer of H and He that remains after an outburst. The thickness of the latter layer varies from outburst to outburst. A thicker layer means a higher heat conductivity which implies a higher observed effective temperature for a given (unchanged) core temperature. However, the luminosity in the soft band in Cen X-4 varies on time scales too short to be explained by variations in the thickness of the H/He layer.

With a long XMM-Newton observation of Cen X-4 one can determine N_{H} by measuring the equivalent width of the oxygen edge observable in the RGS spectrum. In this way N_{H} can be determined independently from the broadband spectral fit to the pn and MOS spectra, leaving only the temperature and normalisation of the soft thermal component and the power-law index and normalisation as free parameters to explain the variability.

There are two possible outcomes of such a study. First, if it is determined that indeed the soft thermal spectral component does not vary and the variability can be explained by coupled variations in the power law and N_{H} it would boost the confidence in the masses and radii that have been and can be determined from fitting the NSA models to the X-ray spectra of quiescent low-mass X-ray binaries. Note that unknown uncertainties in the neutron star atmosphere models remain. However, in this respect it is interesting to note that various atmosphere models give similar results (see discussion in Webb & Barret 2007). In the case of Cen X-4 a parallax distance determination would allow the most accurate determination of the radius of a neutron star to date due to the huge number of photons that will make up the XMM-Newton EPIC pn and MOS X-ray spectra. With a distance of 1.2 ± 0.3 kpc estimated from radius expansion bursts (Chevalier et al. 1989), Cen X-4 is the nearest neutron star X-ray transient currently known.

The second possible outcome is that the soft thermal component varies substantially. This would either mean that there exists a currently unidentified mechanism associated with crustal heating that causes the effective temperature to change on short timescales or that the soft X-ray spectral component is caused by another process such as residual accretion as proposed by van Paradijs et al. (1987) and Zampieri et al. (1995). This would imply that the cores of these neutron stars are so cold that the hot thermal glow is not detectable, providing evidence for enhanced cooling mechanisms in these neutron stars (cf. Jonker et al. 2007 for the case of 1H 1905+000).

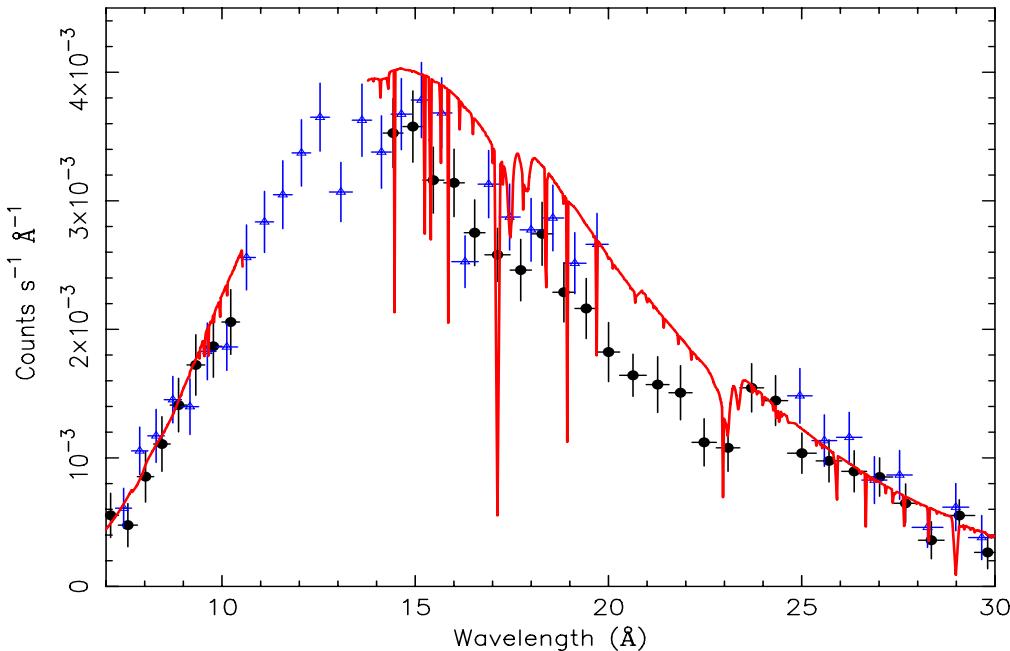


Fig. 1 (online colour at: www.an-journal.org) A simulated RGS spectrum for a 250 ks-long XMM-Newton observation of Cen X-4. The black bullets with error bars are the rebinned simulated RGS-1 data points, the blue open triangles with error bars are the rebinned simulated RGS-2 data points, and the red, drawn line is the model fitted to the RGS-1 data where the oxygen column density is put to zero showing the large difference between the data and the model especially between 15–22 Å. Most of the narrow lines are due to CCD gaps and detector drop outs. Unfortunately, most of the O I K-edge wavelength is not covered by the RGS-2 due to loss of CCD4 in RGS-2. The oxygen column density and, under the assumption of solar abundances, the N_{H} can be determined with an accuracy of 8–9% if the broad band spectral components are held fixed. Such an observation will allow us to determine if indeed the factor of 2–3 variation in N_{H} necessary to explain the luminosity variations as coupled variations in the power law index and N_{H} is present or not (Campana et al. 2003, 2004).

3 Redshifted absorption lines from the neutron star surface

A possible, very important, discovery that might come from deep observations of quiescent low-mass X-ray binaries is that of redshifted absorption lines from the neutron star atmosphere. Currently, redshifted absorption lines might have been detected in the bright accreting low-mass X-ray binary EXO 0748–676 (Cottam et al. 2002). However, with subsequent observations Cottam et al. (2007) could not confirm the existence of the lines in EXO 0748–676. Redshifted lines have also been searched for but not detected in GS 1826–238 (Thompson et al. 2005; Kong et al. 2007).

A potential problem with detecting redshifted absorption lines in quiescent low-mass X-ray binaries is that the accretion rate might be too low. Elements more heavy than He will sink out of the atmosphere too quickly (Bildsten & Rutledge 2001). Furthermore, for all rapidly rotating neutron stars the contrast between the absorption line and the continuum is strongly reduced irrespective of whether the source is in quiescence or not. Therefore, one will only under special viewing inclinations be able to detect absorption lines in these systems (Chang et al. 2006).

We have identified a special class of type I X-ray bursts that might be better suited to search for redshifted metal lines in the atmospheres of neutron stars; radius expansion

bursts from ultra-compact X-ray binaries. The idea behind grating observations of low-mass X-ray binaries showing these type of bursts is that the burst luminosity is higher than that of the bursts used for the searches for absorption line measurements in EXO 0748–676 and GS 1826–238. Furthermore, Weinberg, Bildsten, & Schatz (2006) showed that the ashes of the nuclear burning in radius expansion bursts might contain rare elements that are transported to the surface. These elements could produce absorption lines that can be detected in high resolution X-ray spectra just after the radius expansion phase when the neutron star photosphere settles back on the neutron star.

4 Determination of the eclipse duration

Using Kepler's laws and Newtonian mechanics it has been shown that the mass of a neutron star can be determined via the mass function, $f(m)$: $\frac{M_{\text{NS}} \sin^3 i}{(1+q)^2} = \frac{K_{\text{CP}}^3 \times P}{2\pi G}$. Here, M_{NS} is the mass of the neutron star, G is the gravitational constant, P the binary orbital period, i the binary system inclination, K_{CP} the radial velocity semi-amplitude of the companion star and q is defined here as the ratio between the mass of the neutron star and that of the companion star. K_{CP} and P can be determined through optical spectroscopic measurements of Doppler shifts of the weak stellar

absorption lines as a function of the binary orbital period. To determine the mass q and i need to be measured as well.

Tidal interactions between the neutron star and companion star will quickly bring the latter in co-rotation with the orbital motion. This will ensure that the companion star spins rapidly, which manifests itself in a broadening of the stellar absorption lines. In low-mass X-ray binaries broadening of the stellar absorption lines due to effects other than the rotational velocity of the companion star are at least an order of magnitude smaller. The rotational broadening of the stellar absorption lines can be measured through spectroscopic observations similar to those used to determine K_{CP} . One can derive the following relation between the observed stellar rotational velocity ($v \sin i$) and the mass ratio, q , in these mass-transferring systems: $\frac{v \sin i}{K_{\text{CP}}} = 0.46[(1+q)^2 q]^{1/3}$ (e.g. Wade & Horne 1988).

The only remaining unknown parameter is the system inclination with respect to our line-of-sight, i . If eclipses in the X-ray lightcurve are observed in these low-mass X-ray binaries simple geometrical arguments show that the inclination has to be $i \lesssim 75^\circ$ (Frank, King & Raine 2002). However, knowledge of the mass ratio q and the eclipse duration $\delta\phi$ provides a much more accurate handle on i (Horne 1985). XMM-Newton observations of low-mass X-ray binaries in quiescence can provide the eclipse duration (cf. Nowak et al. 2002).

5 Conclusions

We have identified three possible ways in which XMM-Newton can either lead or have an important role in determining the neutron star EoS. First, a long observation of a neutron star low-mass X-ray binary in quiescence with a flux high enough to allow an RGS spectrum to be extracted is necessary to investigate if indeed the soft thermal spectral component is stationary. If so, and if the distance to the system is accurately known the neutron star mass and radius can be determined from a NSA model fit to the EPIC pn and MOS spectra. Currently, the best source for such a study is Cen X-4. Secondly, one can potentially use radius expansion bursts to search for redshifted absorption lines from the neutron star surface. Again nearby systems are preferred to maximise the source flux. Finally, XMM-Newton observations of eclipsing low-mass X-ray binaries yield the eclipse duration, which together with a measurement of the mass ratio yields an accurate determination of the inclination angle that enters the mass function. Using XMM-Newton observations mass measurements of these eclipsing sources become much more accurate.

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