Fe K emission lines in neutron star low-mass X-ray binaries

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Abstract

Over recent years, *Suzaku* and *XMM-Newton* observations of neutron star low-mass X-ray binaries have uncovered broad, asymmetric Fe K emission lines in these sources. It is believed that the lines arise from irradiation of the innermost accretion disk. Thus, the line profile is skewed by relativistic effects present there, leading to a measure of the inner disk radius. We summarize our comprehensive analysis of the spectra from 10 neutron star low-mass X-ray binaries here. We not only fit simple phenomenological models to the spectra, but also a more self-consistent approach using a reflection model wherein a blackbody provides the irradiating flux. Such a model is appropriate for these sources where a blackbody dominates the spectrum from around $8 - 20$ keV. A realistic geometry for this reflection would involve the boundary layer (the assumed source of blackbody-like emission) irradiating the inner disk. From our modeling, we only find a small range in inner disk radius ($6 - 15$ GM/c^2 in the majority of cases), and find no obvious trend with luminosity. One particularly interesting source is the accreting millisecond X-ray pulsar SAX J1808.4−3658. The Fe K emission line in this source allows us to estimate the magnetic field strength in this system to be $\sim 3 \times 10^8$ G, broadly consistent with previous independent estimates.

Key words: X-rays: binaries — stars: neutron — accretion, accretion disks

1. Introduction

Accretion disks around black holes and neutron stars are unique probes of strong gravity as relativistic effects are prominent in regions close to these objects. Any emission that comes from these close-in regions therefore has these relativistic effects imprinted on it. One particularly noticeable feature of the X-ray spectra from these sources is often a Fe Kα emission line at around 6.4-6.97 keV. In many cases, this line is observed to show an asymmetric profile (see Miller 2007 for a recent review). Such asymmetric profiles are naturally explained if the Fe Kα emitting region is close to the compact object, where relativistic Doppler effects and gravitational redshifts are strong (e.g. Fabian et al. 1989). These effects cause the emission line to be broadened and skewed.

For the most part, there has until recently been more of a focus on Fe Kα emission lines in black hole systems. It is not that the lines do not exist in neutron star low-mass X-ray binaries, they have actually been known of for a number of years (e.g. White et al. 1986, Hiraino 1987, Asai et al. 2000, Di Salvo et al. 2005). But, the reason is two-fold (i) observationally, the lines in black hole systems typically have much higher equivalents widths, and so the characteristic asymmetric profile was more easily observed, and (ii) measuring the inner accretion disk radius around a black hole can lead to an estimate of its spin, one of only two quantities that describe an astrophysical black hole. However, over the last few years, it has become clear that Fe Kα emission lines in neutron star low-mass X-ray binaries also show the characteristic asymmetric line profiles (e.g., Bhattacharyya & Strohmayer et al. 2007; Cackett et al. 2008; Pandel et al. 2008; D'Aì et al. 2009; Cackett et al. 2009a,b; Papitto et al. 2009; Reis et al. 2009, Di Salvo et al. 2009, Iaria et al. 2009). This development has, in no small part, been achieved by using the high effective area and broadband spectral coverage provided by

Suzaku, in addition to *XMM-Newton*. Now, there are clear lines seen in at least 10 neutron star LMXBs (see Cackett et al. 2009b, and references therein), comparable to the number of lines observed in black hole X-ray binaries.

Fe Kα lines in neutron star low-mass X-ray binaries are of particular interest - measuring the extent of the inner disk naturally places an upper limit on the stellar radius. Radius and/or mass constraints for neutron stars are vitally important in determining the equation of state of the ultra dense matter (e.g. Lattimer & Prakash 2004). Moreover, the space-time around a neutron star is very close to the Schwarzschild metric - the innermost stable orbit in the Schwarzschild metric for a mass of 1.4 $M_{\odot}$ corresponds to about 12 km, very close to the expected radius of a neutron star. Furthermore, measuring the inner disk radius in many different states/luminosities may lead to a better understanding of the accretion flow around these objects and its evolution.

Here, we present recent results on Fe Kα line in neutron star low-mass X-ray binaries from *Suzaku* and *XMM-Newton* observations. The work presented here is based on Cackett et al. (2008, 2009a, 2009b). Please see those papers for more details that cannot be included in a short conference proceedings.

2. Reflection in neutron star LMXBs

Before discussing the observations, it is worth discussing 'reflection'. The Fe Kα emission line is just the most prominent feature of a 'reflection' spectrum – hard X-rays irradiate the accretion disk and are reflected back towards our line of sight. Fe Kα is the strongest feature due to its abundance and fluorescence yield, though other lines are also produced at lower energies. Other, more subtle features, including a Compton back-scattering reflection hump between 20-30 keV are also present (e.g., George & Fabian 1991). In black hole sources, reflection has been explored in detail, with a number of models for both neutral and ionized reflection (e.g., George & Fabian 1991; Magdziarz & Zdziarski 1995; Nayakshin & Kallman 2001; Ballantyne et al. 2001; Ross & Fabian 2007). Both the Fe K line and reflection have been clearly revealed in a number of black hole sources of the past decade or so. In these black hole objects, it is assumed that a power-law spectrum of hard X-rays irradiates the disk.

In neutron star low-mass X-ray binaries, reflection has been studied in less detail thus far. The geometry here is also different than the black hole case because of the presence of the stellar surface. The Keplerian frequency of the inner disk is faster than that of the spin of neutron stars, thus as material from the disk reaches the surface it must lose angular momentum. This is thought to happen in a boundary layer, though whether this is a

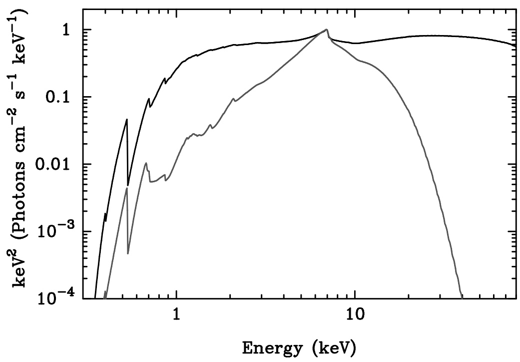

Fig. 1. Blurred reflection models for irradiation by a power-law, $\Gamma = 2$ (black) and a blackbody, kT = 2 keV (gray) both for an ionization parameter of 1000 (models are from Ballantyne et al. 2001 & Ballantyne 2004). The spectra are relativistically blurred assuming an emissivity index $q = 3$, $R_{in} = 10$ GM/c^2, $R_{out} = 1000$ GM/c^2, and inclination = 30°. $N_H = 5 \times 10^{21}$ cm^{-2} was used.

vertically and radially extended region (e.g. Popham & Sunyaev 2001) or a spreading layer on the surface (Inogamov & Sunyaev 1999) remains unclear. However, this boundary layer may act to provide the source of hard X-rays irradiating the disk in these neutron star low-mass X-ray binaries (e.g., Brandt & Matt 1994, Popham & Sunyaev 2001). The boundary layer spectrum should be close to a blackbody when the material is optically thick.

The resulting reflection spectra from a irradiating power-law (as for black holes) and irradiating blackbody (for neutron stars) is quite different (see Fig. 1). Most noticeable, is that the Compton back-scattering hump that one can easily see in the power-law case is hidden by the sharp drop off above 10 keV in the reflected component in the blackbody case. Later in this paper, we will apply the latter model to broadband *Suzaku* spectra.

3. Source sample and data analysis

In our recent paper (Cackett et al. 2009b), we present a comprehensive analysis of 10 neutron star LMXBs, reanalyzing archival data in a systematic way, as well as presenting new observations of several objects. Of the 10 sources, 4 are standard atolls (Ser X-1, 4U1636−53, 4U 1705−44, 4U 1820−30), 4 are Z sources (GX 17+2, GX 340+0, GX 349+2, Cyg X-2) and 2 are accreting millisecond X-ray pulsars (SAX J1808.4−3658, HETE J1900.1−2455), and are also atolls. We looked at both *Suzaku* and *XMM-Newton* observations of these sources, and in several cases there were multiple observations of the same source. For full details of the data reduction, observational details, and original references, please refer to Cackett et al. (2009b). In brief, the data analysis was executed in the standard manner. For the *Suzaku* observations we were careful to excise the core of the point spread function when extracting the spectra in order to reduce pile-up.

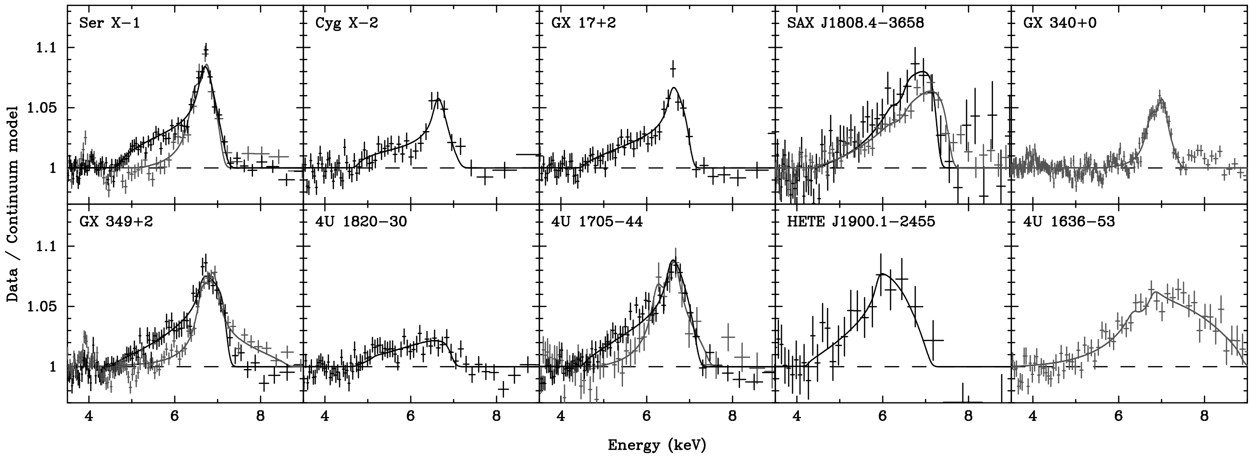

Fig. 2. A summary of Fe K emission lines in neutron star low-mass X-ray binaries, shown as a ratio of the data to the phenomenological continuum model. Data is from *Suzaku* (black) and *XMM-Newton* (gray), and the best-fitting diskline models are shown as a solid line.

Spectral fitting was performed with XSPEC v12. Our spectral fitting approach was two-fold. Firstly, we fitted a phenomenological model, describing the continuum with a model comprising of a multicolor disk blackbody, single temperature blackbody and a power-law (all modified by Galactic absorption), and we ensured that all components were required statistically before adding them to the model. For the Fe K line we used the diskline model (Fabian et al 1989) which is appropriate for a Schwarzschild metric. As the innermost stable orbit in the Schwarzschild metric is close to the expected neutron star radius, and as the dimensionless angular momentum parameter for neutron stars is not close to 1, this line model is appropriate here. A summary of the observed Fe K emission lines is shown in Fig. 2.

The second approach we used was chosen to be more self-consistent. Here, we modeled the continuum in the same way as above, yet instead of using the diskline model to fit the iron line, we included a relativistically blurred reflection model. The reflection model we chose was developed for the case of X-ray bursts where the burst on the neutron star surface illuminates the disk (Ballantyne & Strohmayer 2004, Ballantyne 2004). In that model, a blackbody component irradiates a uniform slab. From the phenomenological fitting, it is clear that a hot single temperature blackbody component is the dominant flux between $\sim 8-20$ keV, and thus is providing the majority of the flux able to ionize Fe. The geometrical picture, then, is one where the boundary layer (whose emission is approximately a blackbody when optically thick) irradiates the inner accretion disk, leading to a reflection component with a prominent Fe K emission line (see Fig. 1). Of course, as this reflected component originates at the inner part of the accretion disk, it is subject to relativistic effects, thus, the reflection component is relativistically blurred (by convolving with the diskline model).

4. Results & Discussion

Rather than present a large number of tables here, we refer the reader to Cackett et al. (2009b) for a complete set of results from all spectral fitting and a more detailed discussion. The measured inner disk radii (for both phenomenological and reflection fits) are shown in Fig. 3. In the cases where there are multiple observations, the one with the smallest fractional uncertainty was chosen. This figure demonstrates the narrow range of inner disk radii that we find. We also show the inner disk radius as a function of 0.5-10 keV source luminosity in Fig. 4. From this, there is no apparent trend of inner disk radius with luminosity.

Modeling of the continuum shows that in the majority of observations, a blackbody component (potentially associated with the boundary layer) dominates the ionizing flux that irradiates the accretion disk. Our reflection modeling that uses an irradiating blackbody component fits the data well in almost all cases (only the millisecond pulsars require a power-law reflection model). This supports the idea that the boundary layer between the inner accretion disk and the stellar surface can illuminate the disk leading to reflection. The reflection fits lead to a measurement of the ionization parameter, which we find to be in the range $\log \xi = 2.6 - 2.8$, though this is natural given that the EW of Fe K peaks at these ionization parameters in this model (Ballantyne 2004).

4.1. Magnetic field estimate in SAX J1808−3658

An interesting source to study is the accreting millisecond X-ray pulsar SAX J1808.4−3658. The discovery of a broadened Fe K emission line in this object (Cackett et al. 2009a, Papitto et al. 2009), allows for an independent constraint on the magnetic field strength (Cackett

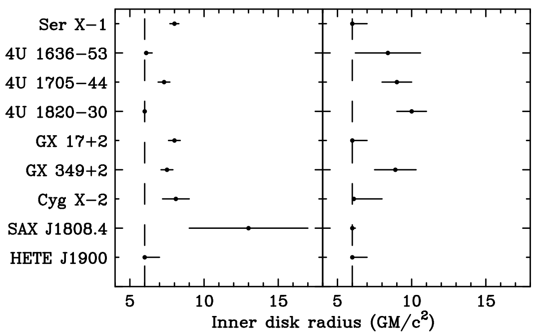

Fig. 3. The measured inner disk radii for phenomenological (left) and reflection (right) models. The dashed line marks the radius of the innermost stable circular orbit for a Schwarzschild metric, and is the lower limit allowed in the model.

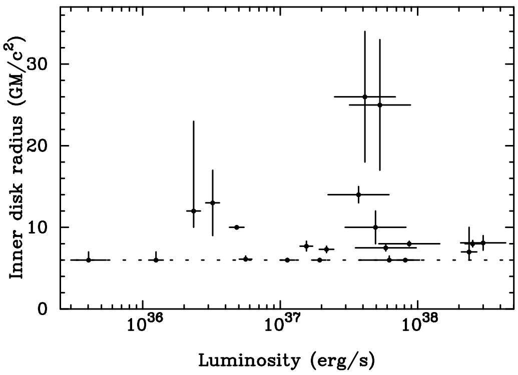

Fig. 4. Inner disk radius from phenomenological fits as a function of 0.5-10 keV luminosity.

et al. 2009a). As the source is known to be pulsating, we can assume that the accretion flow is truncated at the magnetospheric radius. This would allow material to flow along the field lines and onto the stellar surface leading to hotspots and pulsations. If we assume, then, that the inner disk radius measured from the broad Fe K line (13.2 ± 2.5 GM/c^2) is the magnetospheric radius we can estimate the magnetic field strength to be $B = (3.2 \pm 1.0) \times 10^8$ G at the magnetic poles (Cackett et al. 2009a). This compares well with previous, independent estimates (Psaltis & Chakrabarty 1999; Di Salvo & Burderi 2003; Hartman et al. 2008).

Acknowledgments

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