PROCEEDINGS OF SCIENCE

M/R constraints from neutron-star iron lines

María Díaz Trigo[∗a], **Cherry Ng**[b], **Marion Cadolle Bel**[c] **and Simone Migliari**[d]
[a]*ESO, Karl-Schwarzschildstrasse 2, D-85748 Garching bei München, Germany*
[b]*Max-Planck-Institut für Radioastronomie, Auf den Hügel 69, D-53121 Bonn, Germany*
[c]*Integral Science Operations Centre, Science Operations Department, ESAC, PO Box 78, 28691 Villanueva de la Cañada, Madrid, Spain*
[d]*Departament d'Astronomia i Meteorologia, Universitat de Barcelona, Martí i Franquès, 08028 Barcelona, Spain*
E-mail: mdiaztri@eso.org

The recent claim of broad skewed iron lines from neutron star (NS) low-mass X-ray binaries (LMXBs) has opened the exciting possibility of determining an upper limit to the radius of the NS, the most difficult parameter to obtain in order to constrain their equation of state. With the aim of studying further this possibility, we performed a systematic analysis of XMM-Newton archival observations of 16 bright NS LMXBs. We performed a detailed data analysis taking into account the systematic effects that arise as a consequence of the high count rates present in the observations of these sources. The properties of the Fe lines differed from previous published analyses due to either different pile-up corrections or continuum parameterisation. Most importantly, we could fit the Fe line with a simple Gaussian component for all the sources in the sample. The lines did not show the asymmetric profiles that were interpreted as an indication of relativistic effects in previous analyses of these LMXBs. We summarise here the results of the outlined study (for details, see [19]) and discuss the implications of these results for studies of broad Fe lines in LMXBs with current and future missions.

Fast X-ray timing and spectroscopy at extreme count rates
February 7-11, 2011
Champéry, Switzerland

∗Speaker.

PoS(HTRS 2011)026

1. Introduction

Accreting binaries often show Fe line emission in their X-ray spectra. The ability of *Chandra*, XMM-Newton, *Suzaku* and *Swift* to obtain medium- to high-resolution spectra covering the Fe K energy band has opened a new era in the observations of stellar-mass holes (BHs) and NS binaries. The large effective area of these observatories is crucial for detecting Fe line emission, while the high resolution enables us to distinguish between narrow and intrinsically broad features.

The origin of broad Fe lines has been extensively discussed (see e.g. [7, 22, 23]). However, even after the advent of the current powerful X-ray observatories, the exact determination of the line width and the mechanisms responsible for it remain controversial. Undoubtedly, the most exciting possibility is that such lines originate in the disc close to the BH event horizon or to the NS by fluorescent emission following illumination (and photoionisation) of the accretion disc by an external source of X-rays [8, 20]. In this model, the combination of relativistic Doppler effects arising from the high orbital velocities and gravitational effects of the strong gravitational field in the vicinity of the compact object smear the reflected features. Hence, detailed X-ray spectroscopy of Fe line features can be used to study Doppler and gravitational redshifts, thereby providing key information on the location and kinematics of the material in the vicinity of the compact object. Most interesting of all is the potential for establishing BH spin using relativistic Fe Kα lines. The spin value is constrained mainly by the lower boundary of the broad line, which depends on the inner boundary of the disc emission (identified with the marginally stable orbit) where the gravitational redshift is maximal. Therefore, lines that are strongly skewed toward lower energies can indicate black hole spin [11, 18].

The recent claim of broad skewed Fe lines from NS binaries has opened the exciting possibility of determining an upper limit to the radius of the NS, the most difficult parameter to obtain to constrain the equation of state of NSs [2]. The advantage of using Fe K emission lines as a probe of the NS radius is that they only require short observations to clearly reveal the lines and they do not require any knowledge of the distance to the object. A mass determination can be then inferred by combining the radius obtained from fits to the line profile and the frequency of the upper kHz QPO, assuming Keplerian frequencies for such QPOs (see e.g. [17]).

Systematic analyses of broad line emission in NS LMXBs with EXOSAT, Tenma and ASCA [25, 12, 1] revealed a consistent picture in which line emission was found in 50–80% of the objects. The lines had centroid energies of 6.6-6.9 keV and were broad, with FWHM of 0.5-1.3 keV, and equivalent widths (EWs) in the range 10-170 eV. Furthermore, the line properties did not show any obvious correlation with luminosity. The conclusion of these studies was that the only plausible broadening mechanism was a combination of line blending, Doppler broadening, and Compton scattering in a hot accretion disc corona. This picture changed with the claim of skewed Fe lines in observations of NS LMXBs by XMM-Newton, *Chandra* and *Suzaku*.

However, an interpretation of the iron line parameters in the context of relativistic broadening is problematic due to the following reasons: only some of the NS LMXBs have shown such asymmetric lines, while others show symmetric lines [4], a large inclination ($>80^{\circ}$) is derived for sources which do not show dips or eclipses in the spectra [5], different inclinations are derived for the same source at different epochs [5, 6], the parameters depend on the choice of the continuum [2, 5], the model used for the line (e.g. `diskline` or `laor`), and on the broad band coverage

[5] and finally, instrumental effects that are treated differently by different authors may introduce further discrepancies [5, 13].

Hence, a systematic analysis of the Fe K lines is at this stage fundamental to solve the outlined problems and help to clarify the currently controversial origin of the lines. With this aim we analysed 26 observations of 16 different NS LMXBs observed by XMM-Newton since the beginning of the mission and publicly available up to September 30, 2009. We excluded from this sample observations with known inclinations above 70°, since their analyses at the Fe band are complicated by strong absorption in the line of sight.

2. Observations and data reduction

A summary of the XMM-Newton observations is shown in Table 1 of [19]. The EPIC pn was used in timing mode for all the observations. Data products were reduced using the Science Analysis Software (SAS) version 9.0. The EPIC MOS cameras were not used in most of the observations analysed in this paper because their telemetry was allocated to the EPIC pn camera to avoid Full Scientific Buffer in the latter. We did not analyse the RGS data since they do not cover the Fe K energy band in which we are interested.

We used the SAS task `epfast` on the event files to correct for a charge transfer inefficiency (CTI) effect seen in the EPIC pn timing mode when high count rates are present[1]. Ancillary response files were generated using the SAS task `arfgen` following the recommendations of the *XMM-Newton SAS User Guide*[2] for piled-up observations in timing mode whenever applicable. Response matrices were generated using the SAS task `rmfgen`. We extracted one EPIC pn spectrum per observation, not taking any intra-observational variability into account. Bursts were excluded for the calculation of the total energy spectra whenever present.

2.1 Instrumental effects at high count rates

At high count rates a number of instrumental effects such as pile-up and X-ray loading are present in the EPIC pn timing mode observations. These effects cause spectral distortion and should therefore be carefully removed or taken into account before spectral analysis. *Pile-up* occurs whenever more than one X-ray photon arrive in one camera pixel or in adjacent pixels before they are read out. Because of the photon pile-up, soft photons are apparently lost, whose charge combines and is then seen at higher energies. The count rate at which an observation is affected by pile-up depends on the spectral shape of the source. This is due to the effect of *X-ray loading*[3], or inclusion of events in the offset map. X-ray loading occurs when a too large number of X-ray events per pixel is registered during the offset map calculated onboard at the start of each exposure and leads to an incorrect offset shift for the affected pixel. The severity of X-ray loading depends on the sum of the energies of the contaminating events. The existence of both X-ray loading and

[1]More information about the CTI correction can be found in the *EPIC status of calibration and data analysis* and in the current calibration file (CCF) release note *Rate-dependent CTI correction for EPIC-pn timing modes*, by Guainazzi et al. (2008), available at http://xmm.esac.esa.int/external/xmm_calibration

[2]http://xmm.esac.esa.int

[3]More information on X-ray loading in the EPIC pn camera can be found in the Technical Note *PN X-ray loading investigation results* by Smith (2004), available at http://xmm.esac.esa.int

pile-up effects can be investigated with the SAS task `epatplot`, which utilises the relative ratios of single- and double-pixel events deviating from the standard values as a diagnostic tool, since both pile-up and X-ray loading will produce a pattern migration (of single to double events in the first case and of double to single events in the second case). Using this task, we found that the spectra of twelve observations from eight sources were affected by pile-up (see Table 1 of [19]). For those observations we extracted the spectra excluding the columns affected by pile-up.

3. Results

We fitted the EPIC pn spectra with a model consisting of a blackbody and a disc blackbody, one Gaussian emission feature at $\sim$1 keV (or absorption edge at $\sim$0.87 keV), and one emission feature at $\sim$6.5 keV (modelled with Gaussian or `laor`), all modified by photo-electric absorption from neutral material (model `tbabs*(bbodyrad+diskbb+gau`$_1$`+gau`$_2$`(laor))` in XSPEC). The feature at 1 keV has been previously modelled in a number of sources either as an emission line or as an edge, and its nature is unclear [3, 21]. If the feature has an astrophysical origin, its energy is consistent with Ne X or a blend of Fe XX-Fe XXIV emission. When the feature is edge-like, its energy is consistent with O VIII. We fitted the excess at $\sim$6-7 keV with either a Gaussian or a `laor` component (see below). Finally, we added two Gaussian absorption/emission features at $\sim$1.84 keV and $\sim$2.28 keV. Such features probably stem from an incorrect modelling of the Si and Au absorption in the CCD detectors by the EPIC pn calibration, and are not discussed further.

The fits with this model were acceptable for fifteen out of the nineteen observations for which we extracted a spectrum, with χ^2_ν between 0.7 and 1.2 for a number of degrees of freedom (d.o.f.) between 161 and 221. Substituting the blackbody or disc blackbody components in the model by a power law component resulted in fits with similar or worse χ^2_ν for all the observations shown in Table 3 of [19] (see also their Table 6). Substituting the blackbody component by a cutoff power law resulted in fits with similar χ^2_ν. This is expected, since the blackbody in the model accounts for the emission of the boundary layer and could therefore be equally well fitted by a cutoff power law or a `comptt` component, representing saturated Comptonisation. Finally, substituting the disc blackbody component by a cutoff power law resulted in fits with similar χ^2_ν, but with unrealistic values for the index and the cutoff energy of the cutoff power law component. For three of the remaining four observations the quality of the fit improved when substituting the disc blackbody by a power-law component. Finally, for one observation we needed to add a power-law component to the initial model to obtain an acceptable χ^2_ν.

Due to the spectral degeneracy described above, we compared the χ^2_ν for the different continua before adding the emission line at $\sim$6.5 keV to avoid the *EW* of the line being affected by the possible deficiencies of the fit to the continuum. Whenever two different continua yielded a similar χ^2_ν before including the Fe line, e.g. using a disc blackbody in combination with a blackbody or cutoff power law components, the breadth of the line was similar in both fits. In contrast, we found that fits to continua different to the one selected, that yielded significantly higher values of χ^2_ν, had a clear influence on the line breadth for all the sources analysed in this work.

Considering the best-fit continua, we obtained a similar quality for the fits when using a Gaussian or a `laor` component to model the broad emission line at $\sim$6.5 keV. Figure 1 shows the ratio between the data and the best-fit model at the Fe line energy band for all the sources with significant emission when the Fe line is not included.

4. Discussion

We performed a systematic analysis of 26 XMM-Newton observations NS LMXBs observed with EPIC pn timing mode to establish the characteristics of the Fe K line emission in these objects. In seven

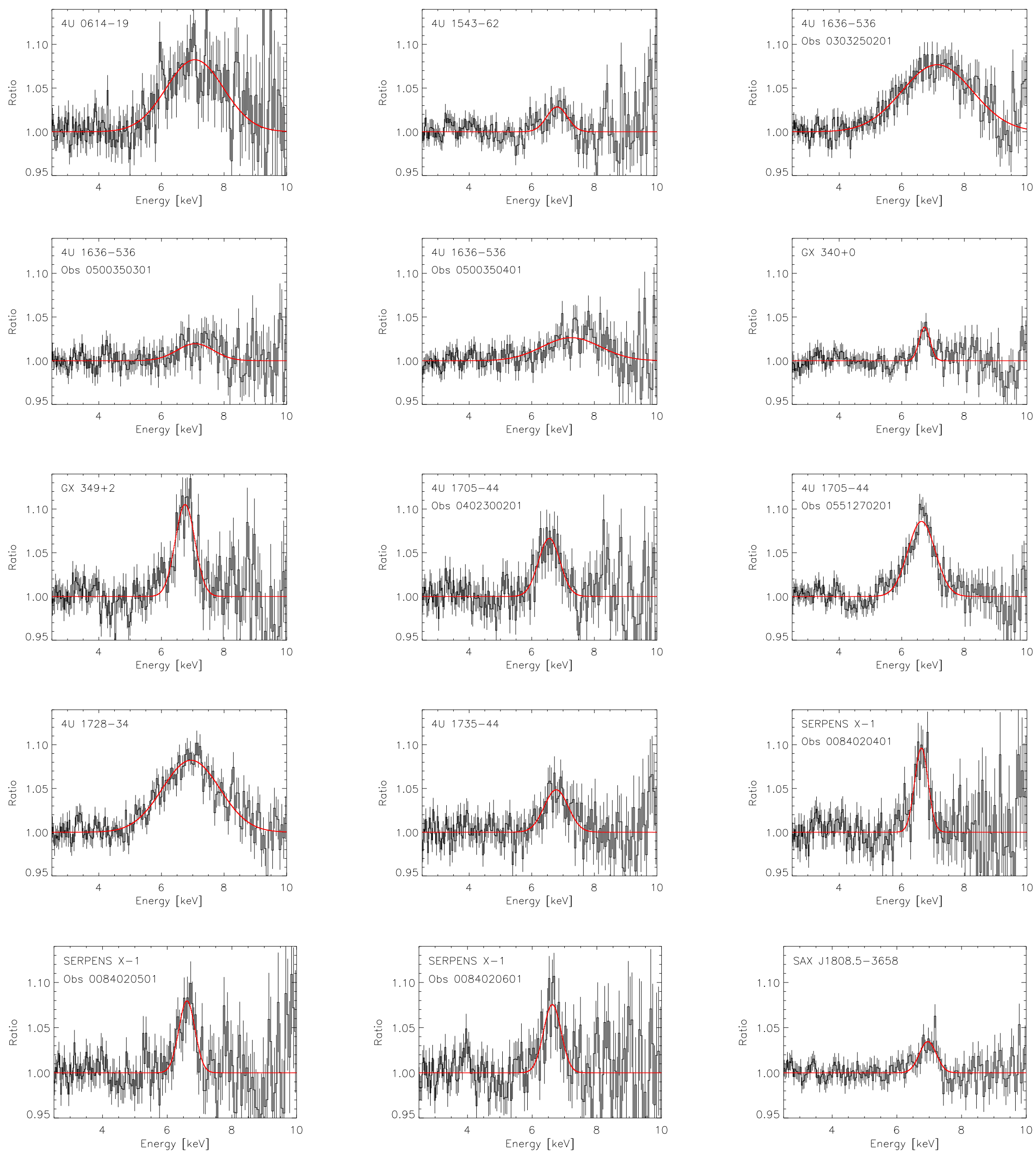

Figure 1: Ratio of the data to the continuum model for all the NS LMXBs analysed in this work [19] for which significant Fe K emission is detected.

observations we did not detect the source significantly. For the remaining 19 observations, we extracted one spectrum per observation. We paid special attention to the effects of pile-up and background subtraction.

We detected Fe Kα line emission in 80% of the observations where the source was significantly detected. The energy of the line had values between 6.53 and 6.97 keV, consistent with highly ionised Fe from Fe XXII to FeXXVI. The width had values between 0.17 and 1.15 keV and the EWs were between 17 and 190 eV. Only in four cases out of the 15 lines reported in this work did we find a width near or above 1 keV and an *EW* above 100 eV. Interestingly, there is a gap in the distributions of σ and *EW* between these high values and the rest of the sample. Lines with high values of σ or *EW* also have large errors associated. In the cases studied here, the lines with widths near 1 keV are in the limit of detectability of 3σ, and the large errors most likely point to an inappropriate modelling of the continuum for 4U 0614+09, 4U 1728−34, and 4U 1636−536. Considering the whole sample, the Fe line has a weighted average energy of 6.67 ± 0.02 keV, a width (σ) of 0.33 ± 0.02 keV, and an *EW* of 42 ± 3 eV.

Recently, broad skewed Fe K emission lines from the disc have been reported from LMXBs containing a NS [2, 5, 13]. All the XMM-Newton observations for which broad skewed Fe lines have been reported were included in our sample. However, in contrast to previous analyses, we *do not* need to invoke relativistic effects to explain its width, which could be due to mechanisms such as Compton broadening. The lines are *equally well* fitted with the relativistic `laor` component or with a simpler Gaussian component. Furthermore, the profiles shown in Fig. 1 do not show any significantly asymmetric shape, as expected if the lines are emitted close to the NS and shaped by relativistic effects. The line profile is instead symmetric, similar to the one found in dipping sources (see e.g. [3]). The major differences between the analysis presented in this work and previous works are a careful treatment of pile-up effects, common in the observations of bright LMXBs, and a different modelling of the continuum in some cases, which has a strong effect on the *EW* of the lines.

In the observations presented here, we do not observe a correlation between the centroid and the width of the Fe line with luminosity, in agreement with a similar systematic analysis based on ASCA observations [1]. In contrast, the three cases for which a large width and EW are measured occur at relatively low luminosities and are actually associated to large errors. This suggests that the physical condition of the line-emitting region is rather similar among the LMXBs.

In NS LMXBs, broad lines could arise in the inner accretion disc by fluorescence following illumination by an external source of X-rays (e.g. the boundary layer where the accretion disc meets the star), and could be broadened by relativistic effects near the compact object [8, 20]. Alternatively, they could originate in the inner part of the so-called accretion disc corona, formed by evaporation of the outer layers of the disc illuminated by the emission of the central object [14, 24] and be broadened predominantly by Compton scattering [22]. A third possibility, is that they originate in a partially ionised wind as a result of illumination by the central source continuum photons and are broadened by electron downscattering in the wind environment [16]. The first interpretation differs from the other two in that Compton scattering does not suffice to broaden the lines to the observed values, hence relativistic broadening has to be invoked. Therefore, to discriminate between the different interpretations *it is fundamental to determine the characteristics of the plasma where the lines originate, mainly its temperature and state of ionisation, by comparison with detailed reflection models*.

Recently, [9] presented new models for illuminated accretion discs and their structure implementing state-of-the-art atomic data for the isonuclear sequences of iron and oxygen and increasing the energy, spatial and angular resolution compared to previous works. They found that in models with intermediate values of the ionisation parameter ($1.5 \lesssim \log(\xi) \lesssim 3.1$), the structure of the gas displayed a two temperature regime: a hot skin ($T > 10^6$ K) close to the surface where the Compton heating and cooling dominated, and a cold region ($T < 10^5$ K) where the photoelectric opacity quickly thermalized the radiation fields. The thickness of the hot skin increased with the illumination and for illumination cases $\log(\xi) > 2.5$ the effects of Compton scattering became more evident and Compton scattering partially smeared the profile of the iron K line [9]. The *EW*s of the Fe K emission line ranged between 400 and 800 eV for the cases with $\log(\xi)$ between 1 and 3 and decreased rapidly for higher values of ξ, with $EW \sim 40$ eV for $\log(\xi) = 3.8$. [10] found that the lines observed in this work [19] could be explained by ionised reflection of the disc (see their Fig. 10). In this model, the breadth of the lines results primarily from the Compton scattering present in the hot atmosphere or corona, and relativistic effects are not included as a broadening mechanism. Unfortunately, reflection models that combine the accuracy of the models from [9] and that are adequate to NS LMXBs are not available yet.

Therefore, awaiting models that allow to account fully for the reflection component during spectral fitting, it should be kept in mind that the continuum may be modified by such reflection and thus values obtained for the temperature or radius of the disc or blackbody components in the current work [19] may not be realistic. A potential problem of spectral fitting with the current available reflection models is that the models do not predict a strong emission feature at $\sim$1 keV, as observed in the majority of sources in our sample [19]. If we interpret such line as emission from iron L, two different emitting zones, one with a large ionisation parameter and one with a low ionisation parameter could be necessary to obtain the observed large L/K ratio [15]. However, even in that case, a large overabundance of iron with respect to solar abundances is required to explain the absence of features at the energies of oxygen or silicon that should arise in the low ionisation zone [15].

We conclude that the major problems preventing an unequivocal detection of relativistic effects in the shape of the broad iron line observed in NS LMXBs are the continuum degeneracy and the lack of appropriate reflection models for spectral fitting. We can attempt to improve the determination of the continuum with broad band coverage, provided that the cross-calibration between the instruments covering the different bands is sufficient. However, the continuum determination is still hampered in current instruments by instrumental effects that arise as a consequence of the high fluxes typical of LMXBs. Clearly, the difference in the shape of the lines, and therefore on the interpretation of their origin, is driven by all these effects. Therefore future missions should have instruments able to cope with high, $\gtrsim$1 Crab, fluxes and extend their energy coverage above 10 keV. In parallel, the development and the use of self-consistent reflection models adequate for LMXBs is fundamental to shape the continuum and account properly for the Comptonisation effects present in the hot disc atmospheres and coronas of these sources. We note that for a certain range of ionisation parameters asymmetric lines are already evident in self-consistent reflection models [9], hence such asymmetry should be considered before modelling relativistic effects. Finally, given the limited energy resolution of the CCD cameras on-board XMM-Newton and *Suzaku*, the presence of absorption into the line of sight may complicate spectral fitting even further. Although absorption is thought to be more important for high-inclination sources, it is also true that absorption lines and edges are being increasingly found in X-ray binaries. The shape of a broad line could be modified by non-resolved absorption. Hence, a high-energy-resolution instrument such as the X-ray Calorimeter Spectrometer planned for the Japanese-led mission *Astro-H* will allow the warm plasma in the line of sight to be resolved and thus a "clean" view of the reflection to be obtained.

References

[1] K. Asai, T. Dotani, F. Nagase & K. Mitsuda, *Iron K Emission Lines in the Energy Spectra of Low-Mass X-Ray Binaries Observed with ASCA*, ApJS, 131, 571

[2] S. Bhattacharyya & T. E. Strohmayer, *Evidence of a Broad Relativistic Iron Line from the Neutron Star Low-Mass X-Ray Binary Serpens X-1*, ApJ, 664, L103

[3] L. Boirin, M. Méndez, M. Dáz Trigo, A. N. Parmar, J. S. Kaastra, *A highly-ionized absorber in the X-ray binary 4U 1323-62: A new explanation for the dipping phenomenon*, 2005, A&A, 436, 195

[4] E. M. Cackett, J. M. Miller, J. Homan, M. van der Klis, W. H. G. Lewin, M. Méndez, J. Raymond, D. Steeghs & R. Wijnands, *A Search for Iron Emission Lines in the Chandra X-Ray Spectra of Neutron Star Low-Mass X-Ray Binaries*, 2009, ApJ, 690, 1847

[5] E. M. Cackett, J. M. Miller, D. R. Ballantyne, D. Barret, S. Bhattacharyya, M. Boutelier, C. M. Miller, T. Strohmayer, R. Wijnands, *Relativistic Lines and Reflection from the Inner Accretion Disks Around Neutron Stars*, 2010, ApJ, 720, 205

[6] T. di Salvo, A. D'Aì, R. Iaria, L. Burderi, M. Dovciak, V. Karas, G. Matt, A. Papitto, S. Piraino, A. Riggio, N. R. Robba, & A. Santangelo, *A relativistically smeared spectrum in the neutron star X-ray binary 4U 1705-44: looking at the inner accretion disc with X-ray spectroscopy*, 2009, MNRAS, 398, 2022

[7] A. C. Fabian, M. J. Rees, L. Stella & N. E. White, *X-ray fluorescence from the inner disc in Cygnus X-1*, 1989, MNRAS, 238, 729

[8] A. C. Fabian, *Broad Iron Lines in AGN and X-Ray Binaries*, 2005, Astrophysics and Space Science, 300, 97

[9] J. García & T. R. Kallman, *X-ray Reflected Spectra from Accretion Disk Models. I. Constant Density Atmospheres*, 2010, ApJ, 718, 695

[10] J. García, T. R. Kallman & R. F. Mushotzky, *X-ray Reflected Spectra from Accretion Disk Models. II. Diagnostic Tools for X-ray Observations*, 2011, ApJ, 731, id.131

[11] B. Hiemstra, P. Soleri, M. Méndez, T. Belloni, R. Mostafa, R. Wijnands, *Discovery of a broad iron line in the black hole candidate Swift J1753.5-0127, and the disc emission in the low/hard state revisited*, 2009, MNRAS, 394, 2080

[12] T. Hirano, S. Hayakawa, F. Nagase, K. Masai, & K. Mitsuda, *Iron emission line from low-mass x-ray binaries*, 1987, PASJ, 39, 619

[13] R. Iaria, A. D'Aì, T. di Salvo, N. R. Robba, A. Riggio, A. Papitto & L. Burderi, *A ionized reflecting skin above the accretion disk of GX 349+2*, 2009, A&A, 505,1143

[14] T. Kallman & N. E. White, *Iron K lines from low-mass X-ray binaries*, 1989, ApJ, 341, 955

[15] T. Kallman, *The Iron L/K Emission-Line Ratio in Photoioinized Gases*, 1995, ApJ, 455, 603

[16] P. Laurent & L. Titarchuk, *Effects of Downscattering on the Continuum and Line Spectra in a Powerful Wind Environment: Monte Carlo Simulations, Analytical Results, and Data Analysis*, 2007, ApJ, 656, 1056

[17] M. C. Miller, F. K. Lamb & D. Psaltis, *Sonic-Point Model of Kilohertz Quasi-periodic Brightness Oscillations in Low-Mass X-Ray Binaries*, 1998, ApJ, 508, 791

[18] J. M. Miller, C. S. Reynolds, A. C. Fabian, G. Miniutti, L. C. Gallo, *Stellar-Mass Black Hole Spin Constraints from Disk Reflection and Continuum Modeling*, 2009, ApJ, 697, 900

[19] C. Ng, M. Díaz Trigo, M. Cadolle Bel & S. Migliari, *A systematic analysis of the broad Iron Kα line in neutron-star LMXBs with XMM-Newton*, 2010 A&A, 522, id.A96

[20] C. S. Reynolds & M. A. Nowak, *Fluorescent iron lines as a probe of astrophysical black hole systems*, 2003, Physics Reports, 377, 389

[21] L. Sidoli, T. Oosterbroek, A. N. Parmar, D. Lumb, C. Erd, *An XMM-Newton study of the X-ray binary MXB 1659-298 and the discovery of narrow X-ray absorption lines*, 2001, A&A, 379, 540

[22] R. A. Sunyaev & L. G. Titarchuk, *Comptonization of X-rays in plasma clouds - Typical radiation spectra*, 1980, A&A, 86, 121

[23] L. Titarchuk, P. Laurent & N. Shaposnikov, *On the Nonrelativistic Origin of Red-skewed Iron Lines in Cataclysmic Variable, Neutron Star, and Black Hole Sources*, 2009, ApJ, 700, 1831

[24] N. E. White & S. S. Holt, *Accretion disk coronae*, 1982, ApJ, 318, 257

[25] N. E. White, A. Peacock, G. Hasinger, K. O. Mason, G. Manzo, B. G. Taylor, & G. Branduardi-Raymont, *A study of the continuum and iron K line emission from low-mass X-ray binaries*, 1986, MNRAS, 218, 129

PoS(HTRS 2011)026