A relativistically broadened iron line from an Accreting Millisecond Pulsar

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Abstract. The capabilities of *XMM-Newton* have been fully exploited to detect a broadened iron Kα emission line from the 2.5 ms Accreting Millisecond Pulsar, SAX J1808.4-3658. The energy of the transition is compatible with fluorescence from neutral/lowly ionized iron. The observed large width (FWHM more than 1 keV) can be explained through Doppler and relativistic broadening from the inner rings of an accretion disc close to the NS. From a fit of the line shape with a diskline model we obtain an estimate of the inner disc radius of $18.0^{+7.6}_{-5.6}$ km for a 1.4 M$_\odot$ neutron star. The disc is therefore truncated inside the corotation radius (31 km for SAX J1808.4-3658), in agreement with the observation of coherent pulsations. From our estimate of the inner disc radius, we infer that the magnetic field of the neutron star is in the range 1–5$\times 10^8$ G.

INTRODUCTION

Much attention has been devoted in this conference to the most recent results obtained by X-ray spectroscopy on the diagnostic possibilities offered by the broad emission features observed in the spectra of accreting collapsed objects, such as Active Galactic Nuclei or Galactic Low Mass X-ray Binaries (LMXB), hosting a Black Hole or a Neutron Star (NS). These features are generally interpreted as fluorescent emission due to the illumination of a geometrically thin, and optically thick, accretion disc by an external hard X-ray source. Their broadness is thus explained in terms of the relativistic Keplerian motion of the reflecting plasma in the accretion disc, under the gravitational influence of the compact object [1]. The shape of the line is determined by the size of the reflecting disc (that is, by its inner radius, R_{in} and by its outer radius, R_{out}), by the index of the radial dependence of the line emissivity, and by the system inclination.

Here we consider the case of SAX J1808.4-3658 (J1808 in the following). This source was the first discovered [2], and thereafter most studied, Accreting Millisecond Pulsar (AMSP). An AMSP is a NS that accretes mass from a low mass companion star ($\lesssim$ 1 M$_\odot$) and shows coherent pulsations at a few milliseconds period. As the NS magnetic field is able to truncate the accretion disc at a radius $R_{in} > R_{NS}$, where R_{NS} is the NS radius, matter accretes only onto a small fraction of the NS surface at the magnetic caps. Pulsations at the spin period of the NS are observed if the magnetic axis is misaligned

with respect to the spin axis.

J1808 is an X-ray transient source, like all the AMSP discovered so far. Since its discovery in 1996 [3], it shows a few weeks long outburst roughly every two years [see e.g. 4, and references therein]. Its broadband X-ray spectrum has been studied using *RXTE* data during its 1998 and 2002 episodes [5, 6, 7, 8]. Its 3.0–150 keV spectrum can be decomposed into a soft component originating from either the NS surface or the disc, and an energetically dominating hard component, interpreted as thermal Comptonization in a hot ($kT_e > 35$ keV) medium [7]. Signatures of disc reflection, such as a 6.5 keV iron emission line and a Compton hump at $\sim$30 keV were also observed [7].

The observation of an emission line broadened by the relativistic motion in the accretion disc is invaluable for theories of accretion onto a pulsar, allowing a direct estimate of one of the key physical parameters, the inner disc radius. This radius represents the lever arm of the spin-up torque applied by the accreting matter on the NS. Motivated by this fact, we obtained a Target of Opportunity *XMM-Newton* observation of J1808 during its latest outburst. We were therefore able to fully exploit the high sensitivity and spectral resolution of *XMM-Newton* to constrain the 6.5 keV line shape.

THE XMM-NEWTON SPECTRUM OF J1808

The 44 ks *XMM-Newton* observation we present here was performed during the latest outburst occurred in 2008 September/October [9]. The continuum spectrum observed by the EPIC-pn camera (1.4–11 keV) is modelled using three continuum components, (i) the disc emission peaking at a temperature of kT_{disc}=0.24(1) keV; (ii) a 0.40(2) keV black body coming from a region of radius 6.8(1) $d_{3.5}$ km, where $d_{3.5}$ is the distance to the source in units of 3.5 kpc [10]; (iii) an energetically dominating hard component, with a power law shape of index $\alpha = 2.08(1)$ in the energy band in which *XMM-Newton* is sensitive. The presence of two soft thermal components to model the low-energy X-ray spectrum has been also reported in the spectra of other similar sources [11, 12]. The pulse shape and the decrease of the pulsed fraction with energy suggest that the blackbody and the hard component originate from the NS surface and from the accretion columns, respectively [13, 14]. The hard component originates in the accretion columns, where the infalling matter is shocked by the interaction with the emergent radiation from below. The NS hotspots provide, in fact, the cool seed photons that downscatter the accreting hotter plasma through inverse Compton [see 11, and references therein].

Considering also the data taken by the Reflection Grating Spectrometers (RGS) in the 0.5–2.0 keV band, we estimate the equivalent hydrogen column of interstellar photoelectric absorption, $nH = 0.214(3) \times 10^{22}$ cm^{-2}. Also an edge at $E = 0.871$ keV, identified with OVIII absorption, is significantly detected.

A clear excess around 6.5 keV is visible in EPIC-pn data (see left panel of Fig.1). If modeled with a Gaussian, a width of $\sigma = 1.1(2)$ keV is obtained. This large width can be explained with disc reflection of the hard continuum component. We thus consider a `diskline` model [1], which accounts for broadening by relativistic motion in the accretion disc near the NS. This model adequately describes the feature, indicating an inner disc radius in the range 6.0–12.4 R$_g$ (corresponding to 12.4–25.6 km for a 1.4 M$_\odot$ NS). The energy of the transition is $6.43^{+0.07}_{-0.09}$ keV and its equivalent width, 120(20)
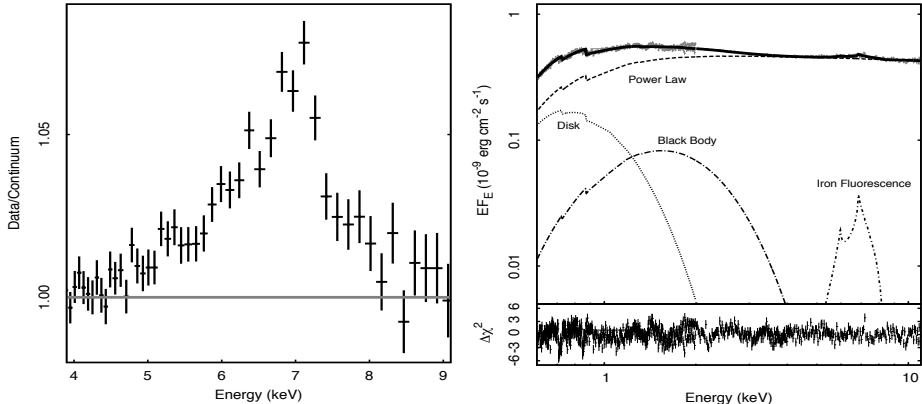
FIGURE 1. Ratio between data and continuum when the 6.5 keV feature is not included in the model (left). 0.6–11 keV unfolded spectrum (right). The components of the best fitting model are also plotted. Spectral bins were rebinned for graphical purposes.

eV. The index of the radial dependence of line emissivity, $\beta = -2.3(3)$, is consistent with a compact illuminating source, and the inclination, $i \gtrsim 60°$, is consistent with estimates made from completely independent arguments [15]. The improvement of the χ^2 when using a `diskline` instead of a Gaussian profile ($\Delta\chi^2 = 13$ for the addition of three parameters over 588 d.o.f.), together with the difficulty of explaining the observed width with alternative scenarios, supports the interpretation of the line profile in terms of disc reflection.

DISCUSSION AND CONCLUSIONS

The spectrum of J1808 observed by *XMM-Newton* is of unprecedented quality for what concerns AMSPs. It allows a firm detection of a broadened iron Kα feature at an energy compatible with neutral or mildly ionized iron. Despite a Gaussian symmetric profile cannot be excluded on a statistical basis, it is hard to find alternatives to relativistic motion of the reflecting plasma in the inner rings of the accretion disc, where the Gravitational field of the NS bends the space-time. Disc reflection is the only viable option to explain such a broad and low ionized feature, in a source whose spectrum is dominated by a Comptonized component originating from a hot, optically thin, medium. The line parameters we obtain are also compatible with those derived by a *Suzaku* observation performed during the same outburst [16].

The estimate we give for the inner disc radius is fundamental to test accretion theories. It allows to estimate where the NS magnetic field truncates the accretion disc. For an accreting pulsar, the inner disc radius R_{in} has to satisfy constraints implied by the presence of pulsations. It has to be larger than the NS radius, $R_{NS} \simeq 10$ km, and not much larger than the corotation radius, defined as the radius where the magnetosphere rotates at the same velocity of disc matter, which is assumed to be in Keplerian rotation.

For J1808 the corotation radius is $R_C = (GMP^2/4\pi^2)^{1/3} = 31m_{1.4}^{1/3}$ km, where $m_{1.4}$ is the NS mass in units of 1.4 $M_\odot$. If the condition $R_{in} \lesssim R_C$ were not met, the magnetosphere would have been spinning more rapidly than the disc at the inner disc radius, and accretion inhibited, or severely attenuated, by the centrifugal barrier [17]. The estimate we give for the inner disc radius from the iron line shape is $R_{in} = 18.0^{+7.6}_{-5.6}$ $m_{1.4}$ km. The lower bound overlaps with the NS radius, while the upper bound is perfectly consistent with the requirement $R_{in} \lesssim R_C$, for any reasonable NS mass. The value we measure can be also compared with theories that express R_{in} in terms of the NS magnetic field strength and of the mass accretion rate [e.g. 18]. Estimating the mass accretion rate from the observed flux, the measured inner disc radius indicates a NS magnetic field in the range 1–5×10^8 G. These values are exactly in the plausible range (10^8–10^9 G) for the AMSPs to be the progenitors of radio millisecond pulsars, according to the recycling scenario [19]. Moreover, they are compatible with estimates made from completely independent arguments [20].

The inner disc radius estimate could have also been useful if the kHz QPOs, already detected from this source [21], were observed in the power spectrum. Unfortunately this was not the case for this observation.

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