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Resolving iron emission lines in 4U 1538-52 with XMM-Newton

Abstract. *We present the results of a XMM-Newton observation of the high-mass X-ray binary 4U 1538-52 at orbital phases between 0.75-1.00 (in the eclipse-ingress phase). Here we concentrate on the study of discrete features in the energy range from 5.9 keV to 7.8 keV, i.e. on the iron* $K\alpha$ *line region, using the EPIC/PN instrument on board XMM-Newton observatory. We clearly see a* $K\alpha$ *neutral iron line at around 6.4 keV and were able to distinguish two hot lines from highly photoionized Fe XXV and Fe XXVI. We discuss the implications of the simultaneous presence of iron with both low and high ionization levels.*

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1. INTRODUCTION

The pulsar nature of the accreting high-mass X-ray binary (HMXB) 4U 1538-52 was discovered by ***Ariel 5*** (Davison 1977) and ***OSO-8*** (Becker et al. 1977), estimating a spin period of 529 s, an orbital period of 3.73 days and evidence of an X-ray eclipse lasting 0.51 days. The binary system consists of a neutron star with a mass of 1.3±0.2 M_{sun} accompanied by a B0 I supergiant star QV Nor with a mass 20±3 M_{sun} (Reynolds, Bell and Hilditch 1992).

An iron emission line has been detected at around 6.4 keV with some X-ray observatories as ***Tenma***, ***RXTE*** or ***BeppoSAX***. This line can be seen both out of eclipse and in eclipse, but only the spectrum in eclipse showed another emission line (Rodes-Roca et al. 2011). Due to the moderate X-ray luminosity $(2\text{-}7)\times10^{36}$ erg/s and the strong stellar wind from the companion, we expect to observe emission lines because of recombination in highly ionized plasma (Day & Stevens 1993).

In this work, we present a spectral analysis of 4U 1538-52 in the 5.9-7.8 keV energy range from an ***XMM-Newton*** observation covering the eclipse ingress. We detect the presence of the Kα neutral iron line at 6.4 keV and the simultaneous presence of the He-like ion of Fe XXV and the H-like ion of Fe XXVI.

2. OBSERVATION

The observation of 4U 1538-52 was carried out using the ***European Photon Imaging Camera*** (***EPIC***) aboard the ***XMM-Newton*** satellite. This source was observed for 55 ks on 2003 August 14-15 (Obs. ID 0152780201). Both the ***EPIC/metal-oxide-semiconductor (MOS)*** and ***EPIC/PN*** instruments (Strüder et al. 2001; Turner et al. 2001) were operated in **Full frame mode**, and the thin filter 1 (MOS-1 and PN) and **medium filter** (MOS-2) were used.

The observation details were summarized in Rodes-Roca et al. (2011, hereafter referred to as Paper I).

The ***EPIC*** observation data files were processed using **Science Analysis System (SAS) version 11.0**, following the standard procedure for XMM-Newton spectra, described in detail in Paper I.

3. SPECTRAL ANALYSIS

Both spectra in eclipse and out of eclipse were rebinned with a minimum of 20 counts per bin and were fitted in the energy range 5.9-7.8 keV using XSPEC version 12.5.0 (Arnaud 1996), released as a part of XANADU in the HEASoft tools. In the following, all spectral uncertainties and upper limits are given at 90% confidence level for one interesting parameter.

On the other hand, due to its higher count rate we used only the ***PN*** spectra to pin down the parameters of both in eclipse and out of eclipse.

3.1. X-ray continuum and emission lines in the eclipse spectrum

Initially we fitted the 5.9-7.8 keV energy spectrum corresponding to the eclipse (orbital phases 0.83-1.00) using an absorbed power-law model to describe the local continuum. Then we added emission lines using Gaussian profiles to fit them. The photoelectric absorption cross sections of Balucinska-Church & McCammon (1992) and the solar abundances of Anders & Grevesse (1989) were used throughout the analysis.

We fixed the hydrogen column density to $N_H = 1.08\times10^{22}$ cm^{-2} and the photon index to 1.74, as obtained in Paper I from the total energy range. In Figure 1, we show the spectrum and the residuals with respect to the best-fit model, an absorbed power-law plus three emission lines using Gaussian profiles, in the 5.9-7.8 keV energy range. Evident is the presence of a Kα neutral iron emission line at $6.400^{+0.014}_{-0.016}$ keV with a width of 75^{+23}_{-12}

eV and two hot lines from highly ionized species of Fe XXV and Fe XXVI. The energies of these lines are 6.69±0.03 keV and $6.97^{+0.04}_{-0.03}$ keV, with corresponding widths less than 157 and 145 eV, respectively. In Table 1 we report the parameters both of the continuum model and of the iron emission lines. The parameters of the Gaussian emission lines are Energy, σ and EW, indicating the centroid, the width and the equivalent width, respectively. We note that the normalization of the power-law component is in units of photons keV^{-1} s^{-1} cm^{-2} at 1 keV.

The measured line energy is consistent with an ionization stage up to Fe XVI, and this requires the ionization parameter ξ should be less than some hundreds (Kallman & McCray 1982; Ebisawa et al. 1996).

On the other hand, the simultaneous presence of the Fe XXV and Fe XXVI lines in the spectrum imply an ionization parameter for the photoionized plasma of $\xi \sim 10^{3.4}$ erg cm s^{-1} (Ebisawa et al. 1996).

Component	**Parameter**	**PN**
Continuum	Photon index	1.74 (frozen)
	Normalization ($\times 10^{-3}$)	$1.38^{+0.12}_{-0.10}$
	N_H (10^{22} cm^{-2})	1.08 (frozen)
Fluorescence iron line	Energy (keV)	$6.400^{+0.014}_{-0.016}$
	σ (eV)	75^{+23}_{-12}
	EW (eV)	580^{+70}_{-90}
	I (10^{-5} photons cm^{-2} s^{-1})	$4.8^{+0.6}_{-0.8}$
Identification		Fe Kα I-XVI
Other iron emission lines	Energy (keV)	6.69 ± 0.03
	σ (eV)	<157
	EW (eV)	160^{+80}_{-30}
	I (10^{-5} photons cm^{-2} s^{-1})	$1.8^{+1.0}_{-0.3}$
Identification		Fe XXV Heα

Component	**Parameter**	**PN**
Other iron emission lines	Energy (keV)	$6.97^{+0.04}_{-0.03}$
	σ (eV)	<145
	EW (eV)	190^{+40}_{-70}
	I (10^{-5} photons cm^{-2} s^{-1})	$1.4^{+0.3}_{-0.6}$
Identification		Fe XXVI
	Chi^2(dof)	50(47)

Table 1. Results of the spectral fit (in eclipse)

3.2. X-ray continuum and emission lines out of the eclipse spectrum

In order to compare spectral parameters, we also obtained the 5.9-7.8 keV energy spectrum corresponding to out of the eclipse (orbital phases 0.75-0.83). We also fitted the local continuum using an absorbed power-law and fixed the photon index to 1.134, as obtained in Paper I. In Figure 2, we show the spectrum and the residuals with respect to the best-fit model, an absorbed power-law plus two emission lines using Gaussian profiles, in the 5.9-7.8 keV energy range. Evident is the presence of a Kα neutral iron emission line at $6.398^{+0.010}_{-0.011}$ keV with a width of 59^{+20}_{-14} eV and one hot line from highly ionized specie of Fe XXV. The energy of this line is $6.699^{+0.013}_{-0.03}$ keV, with corresponding width less than 70 eV. In Table 2 we report the parameters both of the continuum model and of the iron emission lines.

Component	**Parameter**	**PN**
Continuum	Photon index	1.134 (frozen)
	Normalization (×10^{-3})	3.7±0.5
	N_H (10^{22} cm^{-2})	48±5
Fluorescence iron line	Energy (keV)	$6.398^{+0.010}_{-0.011}$
	σ (eV)	59^{+20}_{-14}
	EW (eV)	220^{+30}_{-24}
	I (10^{-5} photons cm^{-2} s^{-1})	4.6±0.5
Identification		Fe Kα I-XVI
Other iron emission lines	Energy (keV)	$6.699^{+0.013}_{-0.03}$
	σ (eV)	<70
	EW (eV)	50^{+23}_{-40}
	I (10^{-5} photons cm^{-2} s^{-1})	$1.2^{+0.6}_{-0.3}$
Identification		Fe XXV Heα
	Chi^2(dof)	134(173)

Table 2. Results of the spectral fit (out of eclipse)

4. DISCUSSION

We have shown that the 5.9-7.8 keV energy range spectrum can in both cases, i.e. in and out of eclipse, be represented by an absorbed power-law adding some Gaussian emission lines. The intensity of the Fe Kα line at 6.4 keV is constant within uncertainties, suggesting that the formation region of the fluorescence line is not far from the compact object. On the other hand, the increase of the EW can be produced when the 6.4 keV line emission region is larger than the opaque body which occults the direct emission from the compact object (Inoue 1985). For iron to produce fluorescent lines at 6.4 keV, the ionization degree of iron should be less than sixteenth, and this requires $\xi \leq 10^2$ erg cm s^{-1} (Kallman & McCray 1982).

The intensity of the line at 6.69 keV decreases slightly from out of eclipse to in eclipse spectrum, as well as the EW. The simultaneous presence of Fe XXV and Fe XXVI lines in the spectrum out of eclipse indicates an ionization parameter for the photoionized plasma of $\xi \sim 10^{3.4}$ erg cm s^{-1} (Ebisawa et al. 1996). The 6.97 keV line is a recombination line produced when Fe XXVII, i.e. iron fully ionized, captures an electron and recombines to Fe XXVI. Therefore, its presence suggests an extremely high ionization state in which iron nuclei are abundant.

The helium-like ion produces three lines at 6.63 keV, 6.67 keV and 6.70 keV, corresponding to the Fe XXV triplet, which are not resolved with PN. Finally, we note that we did not see the Fe XXVI line at 6.9 keV out of the eclipse indicating a lower ionization parameter than the estimated in the eclipse.

The line flux ratio $I_{[\mathrm{Fe\ XXVI}]}/I_{[\mathrm{Fe\ XXV}]}$ is 0.29 for the eclipse, which is around twice the expected ratio for an optically thin plasma (Kaastra & Mewe 1993).

The differing ionization parameter values imply either different distances from the illuminating source or different densities of the illuminated gas. Our results suggest an onion-like structure of the matter around the neutron star.

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