Abstract. We present the results of a series of XMM–Newton EPIC and OM observations of Her X-1, spread over a wide range of the 35 d precession period. We confirm that the spin modulation of the neutron star is weak or absent in the low state - in marked contrast to the main or short-on states. The strong fluorescence emission line at \( \sim 6.4 \) keV is detected in all observations (apart from one taken in the middle of eclipse), with higher line energy, width and normalisation during the main-on state. In addition, we report the detection of a second line near 7 keV in 10 of the 15 observations taken during the low-intensity states of the system. We discuss these observations in the context of previous observations, investigate the origin of the soft and hard X-rays and consider the emission site of the 6.4keV and 7keV emission lines.

INTRODUCTION

Her X-1 is one of the best studied X-ray binaries in the sky. The binary system consists of a neutron star and an A/F secondary star. It has an orbital period of 1.7 d and the neutron star spin period is \( \sim 1.24 \) s. It is one of only a few systems which shows a regular variation in X-rays, over a “beat” period of 35 d, which is generally interpreted as the precession of an accretion disk that periodically obscures the neutron star beam. The cycle comprises: i) a 10 d duration main-on state, ii) a fainter 5 d duration short-on state, and iii) a period of lower emission in between. Exceptions to the normal 35 d cycle has been observed only in four occasions: in 1983, 1993, 1999 and in January 2004 the turn-on of the source has not been observed. During these "anomalous low states" (ALS; the period of which ranges from several months to 1.5 years) Her X-1 appears as a relatively faint X-ray source, with a strength comparable to that of the standard low state. The event registered last year was only the fourth one that has been seen since the discovery of Her X-1 in 1972, and the first one that could be observed with a high capability satellite as XMM–Newton.

Her X-1 has been observed by XMM–Newton on 15 separate occasions outside the ALS, giving good coverage over the beat period. Moreover, it has been observed 10
TIMING ANALYSIS

We first focussed on datasets taken before the source entered the anomalous low state. We performed a search for pulsations in all datasets, confirming that, in marked contrast to the main or short-on states, the spin modulation of the neutron star is weak or absent in the low state. During the states of higher intensity, we observe a substructure in the broad soft X-ray modulation below $\sim 1$ keV, revealing the presence of separate peaks which reflect the structure seen at higher energies (see Ref. [3]).

The soft and hard X-ray lightcurves of Her X-1 are known to be shifted in phase (see Fig. 2, central panel). Under the assumption that soft X-rays are due to the reprocessing of the pulsar beam by the inner edge of the disk, this is usually interpreted as evidence for a tilt angle in the disk [4], [5]. In our XMM–Newton data, we find the first evidence for a substantial and systematic change in the phase difference along the beat cycle, which is predicted by precessing disk models [6] (see Fig. 1).

THE FE Kα LINE

The strong emission line at $\sim 6.4$ keV is detected in all our XMM–Newton observations, with larger broadening and normalization during the main-on (see Fig. 2 left panel). The line centroids observed using the EPIC PN deviate by 4$\sigma$ from the 6.40 keV neutral value: the Fe line emission originates in near neutral Fe (Fe XIV or colder) in the low and short-on state observations, whereas in the main-on the observed Fe Kα centroid energies ($6.65 \pm 0.1$ keV and $6.50 \pm 0.02$ keV at $\Phi_{35} = 0.02$ and 0.17) correspond to Fe XX-Fe XXI [7].

Possible reasons for this behaviour may be: 1) an array of Fe Kα fluorescence lines exists for a variety of charge states of Fe (anything up to Fe XXIII); 2) Comptonization from a hot corona for a narrower range of charge states centered around Fe XX; 3) Keplerian motion. The Keplerian velocity measured at $\Phi_{35} = 0.02$ and 0.17 is $\sim 15500$
and $\sim 13000$ km/s, respectively. This gives a radial distance of $\sim 2 - 3 \times 10^8$ cm, which is close to the magnetospheric radius for a magnetic field of $\sim 10^{12}$ G.

However, another possibility is that the region responsible for the Fe Kα line emission is different for lines observed at different beat phases. In fact, while data taken during the main-on clearly indicate a correlation between the fluorescent Fe Kα line and the soft X-ray emission (Fig. 2, central panel), suggesting a common origin in the illuminated hot spot at the inner edge of the disk, the same is not explicitly evident in data taken during the low state. Instead, at such phases the Fe Kα line is a factor $> 5$ weaker and is clearly modulated with the orbital period (see again Fig. 2, right panel). The correlation between the fast rising UVW1 flux and the Fe Kα detected outside the main-on point to
FIGURE 3. The spectral region around 6.6keV from $\Phi_{35}=0.02$ (top) and $\Phi_{35}=0.79$ (bottom). In both panel a solid line shows the best fit after the normalisation of the one or two Gaussian components have been set to zero.

A fraction of the Fe Kα emission may arise from relatively cold material in a disk wind, such as commonly observed in cataclysmic variables [8]. However, we do not detect the Fe Kα line during the middle of the eclipse, and the upper limit on the line flux is $\sim 10$ or less of that measured outside the eclipse. Also, there is no Doppler signature of a wind in the HETG spectrum of the Fe Kα line [10]. On the other hand, the data reported here suggest a complex origin for the overall emission of the Fe Kα line. To our knowledge, a complex of lines which include all ionization states from Fe XVIII to XXIV Fe Kα has not been observed in any astrophysical source. This may still indicate an outflow of relatively cold gas or some complex dynamics in the disk/magnetosphere interface. Such phenomena should be time-dependent and may be monitored in the future using Astro-E2.

THE $\sim 7$ KEV FE LINE

$XMM$–$Newton$ data have revealed, for the very first time for this source, the presence of a second Fe line at $\sim 7$ keV. The feature is only detected during the low and short-on states, and over several beat phases (see Fig. 3). Also, it has been confirmed by a $Chandra$ HETGS observation of the source (the only one made during the low state) taken at $\Phi_{35} = 0.44 - 0.46$ [10].

The feature cannot be produced by fluorescence, and it is more likely to be a Fe XXVI line originating in widely extended photo-ionized plasma. This is consistent with the fact that also RGS data taken during the low and short-on states show the presence of photo-ionized gas [2]. Grating spectra exhibit several narrow recombination emission lines, the most prominent being C VI, N VI, N VII, O VII, O VIII and Ne IX. The line ratio $G = (f + i)/r$, as computed for all the helium-like ion complexes, is $G \simeq 4$, which indicates that photoionization is the dominant mechanism. Moreover, RGS spectra shows two radiative recombination continua of O VII and N VII, consistent with a low temperature of the emitting plasma ($30000 K < T < 60000 K$) [2]. None of these features is detected during the main-on state.
The recombination X-ray line emission are not likely to originate in HZ Her, due to the absence of UV induced photoexcitation signatures in the He-like triplets (observed with HETGS) [10]. Instead, we propose that an extended, photoionized accretion disk atmosphere may be responsible for such features [2]. The evidence for the disk identification relies on the modeled structure and spectra from a photoionized disk, which is in agreement with the limit set spectroscopically on the density of the low-energy lines emitting region. This theoretical model has been developed by Ref. [9], who computed the spectra of the atmospheric layers of a Shakura-Sunyaev accretion disk, illuminated by a central X-ray continuum. They found that, under these conditions, the disk develops both an extended corona which is kept hot at the Compton temperature, and a more compact, colder, X-ray recombination-emitting atmospheric layer (see Figure 9 in Ref. [2]).

Interestingly, we find that the Fe XXVI line detected by XMM–Newton may be a signature of the hottest external layers of the disk corona, which are located above the recombination-emitting layers. Again, the computed values of the density agree with the constraints inferred from the 7 keV line parameters [3].

In summary, most of the spectral lines discovered with EPIC and RGS can be associated with the illuminated atmosphere/corona of the accretion disk, which explains why they are more prominent during the low states when the direct X-ray beam from the pulsar is obscured by the accretion disk. Therefore, the variability of the Her X-1 spectrum lends support to the precession of the accretion disk, strengthen the interpretation of the low state emission in term of an extended source and open the exciting possibility to monitor spectroscopically the different atmospheric components of the disk during the transition from the low to the high state.

THE ANOMALOUS LOW STATE

Anomalous low states are rare and peculiar events, during which the source resides in a deep low state. While the mechanism that forces state changes is almost certainly variations in accretion disk structure, the engine ultimately driving structural evolution remains unknown. Each past anomalous low state, including the most recent one of January 2004 [11], has been preceded by a period of enhanced spin-down, that has been interpreted in terms of an increasing torque leading to a reversal in the rotation of the inner disk. This also implies that the onset of an anomalous low state is accompanied by a large variation in the structure of the inner region of the accretion disk, that becomes increasingly warped.

In order to search for residual evidence of a 35 d cycle, we compared the line emission detected during the ALS with that observed in the several XMM–Newton datasets we have accumulated during the standard 35 d cycle. As we can see from Fig. 2, as far as the Fe complex is concerned, there is no an obvious difference in the spectral properties of the ALS and of the standard low states. The line features are consistent with being the same in these epoches and the orbital variation of the Kα Fe line shows the same correlation with the UVW1. This supports our scenario in which the Fe line emission of the low state originates in an extended component (disk atmosphere/corona and/or
companion) instead that in the inner region of the disk. Moreover, it is consistent with the fact that at higher energies a significant Compton reflection component has been detected by RXTE in the spectrum of the ALS ([12]).

A detailed comparison of the recombination emission lines measured by RGS can shed more light on this issue. If our interpretation is correct, by measuring the line ratios during the anomalous low state allows to infer the ionization state of the plasma, column density and optical depth in the visible portion of the disk atmosphere/corona, ultimately constraining the accretion geometry.

**REFERENCES**

1. Ramsay, G., et al., *MNRAS*, **337**, 1185, (2002).
2. Jimenez-Garate, M.A., et al., *ApJ*, **578**, 391 (2002)
3. Zane, S., et al., *MNRAS*, **350**, 506 (2004)
4. Oosterbroek, T., et al., *A&A*, **327**, 215 (1997)
5. Oosterbroek, T., et al., *A&A*, **353**, 5755 (2000)
6. Gerend, B., & Boynton, P. *ApJ*, **209**, 562 (1976)
7. Palmeri, P., et al., *A&A*, **403**, 1175 (2003)
8. Drew, J. *IAU colloquium 197, Accretion Phenomena and Related Outflows*, editeb by D.T. Wickramasinghe, L. Ferrario, & G.V. Bicknell (ASP Conf. Ser., 121; San Francisco:ASP), 1997, pp.465
9. Jimenez-Garate, M.A., et al., *ApJ*, **558**, 448 (2001)
10. Jimenez-Garate, M.A., et al., *ApJ* accepted (2005), astro-ph/0411780
11. Still, M. & Boyd, P., *ApJ*, **606**, L135 (2004)
12. Still, M. & Boyd, P., American Astronomical Society, HEAD meeting #8, #33.02, (2004)