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Iron line and continuum flux variations in the *RXTE* X-ray spectra of XTE J1650–500: indications for gravitational light-bending?

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Abstract. We present the results of spectral fits made to 57 pointed observations of the Galactic black hole candidate and X-ray transient XTE J1650−500, made with Rossi X-ray Timing Explorer during its 2001/2002 outburst. A strong and variable Fe Kα emission line is detected in these spectra. The line flux varies in a non-linear way with the hard X-ray flux (modelled with a simple power-law), apparently in contradiction to the predictions of simple disk reflection models. The line flux versus hard X-ray flux variations are remarkably similar to the trend predicted by a recent model which considers gravitational light bending near to a spinning black hole. We also find that changes in the continuum X-ray spectrum, changes in the fast X-ray flux variability, and changes in the line flux versus hard X-ray flux trend coincide. We discuss these results in the context of black hole state transitions.

Key words. accretion, accretion discs – black hole physics – relativity – X-rays: individual (XTE J1650–500) – X-rays: stars

1. Introduction

The energy spectra of several black hole candidates and active galactic nuclei (AGN) show evidence of broad, relativistic iron emission lines (Martocchia et al. 2002, Miller et al. 2002a,b,c , Tanaka et al. 1995, Wilms et al. 2001, Fabian et al. 2002). In standard reflection models, the iron line is produced as the result of the reprocessing of hard X-ray emission by cold material in the accretion disk (e.g. George & Fabian 1991). In such a scenario, variations in the line strength are expected to correlate linearly with those in the hard X-ray flux. However, the spectral variability of some AGN shows that the iron line does not always directly trace variations in the hard X-ray flux (Shih et al. 2002, Lamer et al. 2003, Fabian & Vaughan 2003). Miniutti (2003) proposed a simple model in which gravitational light bending is able to account for that non-trivial behavior.

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Here we present a study of the variations in the spectral properties of the black hole candidate XTE J1650–500 observed by *RXTE* during the first 30 days of its 2001/2002 outburst and we interpret them in the framework of the light-bending model.

2. Observations and Results

2.1. Data Analysis

We used 57 pointed *RXTE* observations of XTE J1650–500 covering the period between 2001 September 6 and 2001 October 5. The evolution of the spectral and variability properties show that this period includes the transition from the hard state to the very high state and the very high state itself (Homan et al. 2003, Rossi et al. 2003, 2004). For our spectral analysis, we combined PCA and HEXTE data to obtain 3-150 keV energy spectra. All the spectra were fitted with a combination of a (cut-off) power law, a multicolor disk blackbody, a smeared edge and a relativistic iron emission line (for an example fit see Fig. 1)

2.2. Results

The top panel of Fig. 2 shows the evolution of the unabsorbed total flux (filled circles), the power-law flux (open circles) and the Fe line flux (crosses), all in the 2–100 keV energy range; in the bottom panel, we show the evolution of the power-law index Γ. This parameter showed two distinct trends: between Sep. 6 and Sep. 18, it rose smoothly from 1.3 to 2.3, after Sep. 19 it remained almost constant around this value. The dotted line in Fig. 2 marks the separation between these two trends; it can be seen that it marks also a change in the source emission. At the beginning, the total flux was dominated by the power-law emission(3.2×10^{-8} erg s^{-1} cm^{-2} at the peak, with a fractional contribution of 95%). Its contribution gradually decreased with time while the total flux decayed. On Sep. 18, the power-law emission had dropped by a factor of ~4 and contributed 67%. After Sep. 19, the total flux decay slowed down less and the contribution of the power-law component is around 50%. The

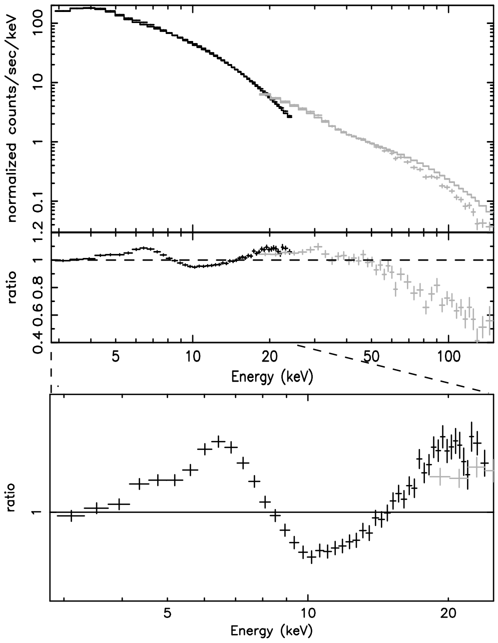

Fig. 1. Fit of the 3-150 keV energy spectra (PCA in black, HEXTE in grey) of XTE J1650−500 on Sep. 13 (top panel). The ratio between the data and the model, consisting of a simple disc black body and a power-law (medium and bottom panels), shows the presence of the high-energy cut off, the Fe Kα emission line and the Fe absorption edge

Fe line flux contributed around 10^{-3} to the total flux; the remaining flux was due to the disk component. From Fig. 2 we can see that, before Sep. 19, the spectral evolution of the Fe line did not follow the power-law, whereas after there was evidence of a positive correlation.

2.3. Relationship between the ionization flux and the reflection component

Within the framework of reflection models, the power-law and Fe line flux variations trace the spectral evolution of the corona and the reflection component, respectively. To explore in more detail the relationship between these two components in XTE J1650–500, we obtained the power-law flux in the 10-100 keV energy band from our fits. This flux (labelled

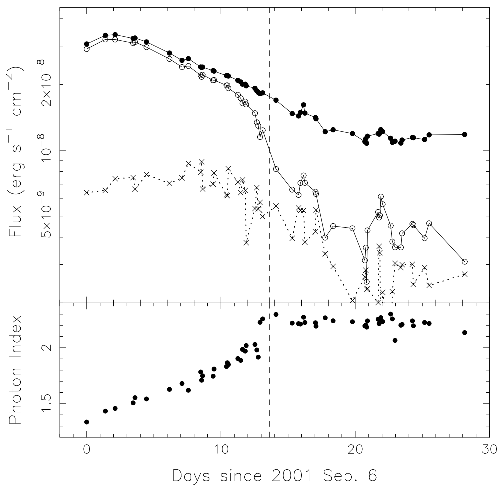

Fig. 2. Evolution of the unabsorbed total flux (filled circles), the power-law flux (open circles) and the Fe-line flux (crosses) in the 2-100 keV energy band. The Fe-line flux is multiply by a factor of 50 (top panel). Evolution of the power-law photon index Γ (bottom panel). The parameters are plotted between 2001 Sep. 6 and Oct. 5; the dotted line marks the changes in spectral parameters after Sep. 19

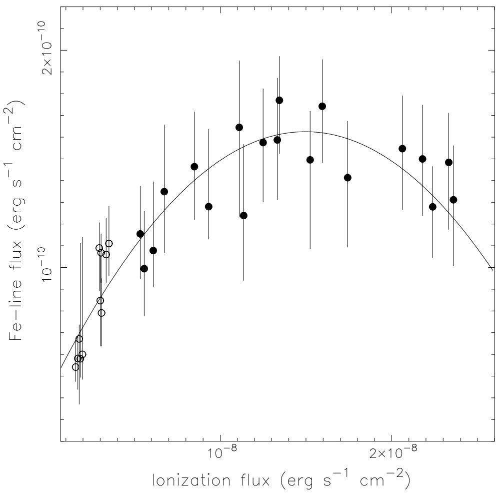

Fig. 3. Fe-line flux in the 2-100 keV energy band in function of the power-law flux in the 10-100 keV energy band, labelled as ionization flux. The error is calculated from the 1σ error on the Fe-line normalization; only the values with $N_{Fe}/\Delta N_{Fe} \geq 2.0$ are shown. The filled circles mark the period between Sep. 6 and Sep. 18, the open circles mark the data between Sep. 19 and Oct. 5

as ionization flux) represents the fraction of the hard X-ray photons which are able to ionize Fe I–XXVI atoms and excite the corresponding emission lines. The fraction of this flux with respect to the total power-law flux is around 80% in almost all observations. In Fig. 3, we show the line flux as a function of the ionization flux using different symbols for observations before (filled circles) and after Sep. 19 (open circles).

The behavior shown in Fig. 3 indicates that the line flux does not evolve in a simple correlated way with the variations in the illuminating flux and indicates that the relationship between these two components changes during the period of our analysis. Qualitatively, before Sep. 19, the line flux shows little variations over a large range of ionization flux, while there is evidence of a positive correlation after Sep. 19. In the scenario of simple reflection models, one expects that the line varies in a linear way with the ionization flux. An analytic fit with a linear function results in a $\chi^2_{red}/d.o.f.$ of 1.57/28. Adding a quadratic term gave a $\chi^2_{red}/d.o.f.$ of 0.57/27. An F-test shows that this improvement was significant at a 5.5σ level. Our best quadratic fit was:

$$y = -5.3\times10^{5}x^{2} + 1.6\times10^{-2}x + 4.3\times10^{-11} \quad (1)$$

and it is represented by the line in Fig. 3.

3. Discussion

Our results show that in XTE J1650–500 the Fe-line flux is not linearly dependent on the power-law flux, which is inconsistent with the predictions of simple disk reflection models. The behavior shown in our Fig. 3 is qualitatively very similar to that shown in Fig. 2 of Miniutti & Fabian (2004). In their model, the observed variability of the Fe-line flux is due to changes in the height h_s of a constant-flux hard X-ray source above a spinning black hole in the center of an accretion disk. They identified three regimes in which the variations in the direct continuum and the Fe-line flux are correlated, independent or anti-correlated, depending whether h_s is low, medium or high, respectively.

The variability of the Fe line of XTE J1650–500 is in good agreement with that predicted in the light bending model. In the framework of this model, the variability of the hard and reflected components observed in spectra from the early phase of its 2001/2002 outburst can be explained by the motion of the hard X-ray source above the accretion disk: in the beginning, the hard X-ray source is located at a medium distance, then it gradually approaches to the disc reaching very short distances after Sep. 19. Using the predictions of Miniutti & Fabian (2004) and assuming that XTE J1650–500 has an inclination of 45°, the height of the hard X-ray source before Sep. 19 is in the range of $2 - 4r_g < h_s < 7 - 13r_g$ and reaches values lower than $\sim 4r_g$ after Sep. 19.

It is worth noting that the point at which the Fe line variations change regime (Sep. 19) coincides with the point at which 250 Hz QPOs are first observed (Homan et al. 2003). In so far as the physical scenario described in the light-bending model naturally corresponds to the base of a jet changing its height, our results suggest a natural link between three phenomena commonly associated with hard X-ray emission: Fe lines, QPOs, and jets.

Our results suggest that the light-bending model may be able to account for the mixture of extreme phenomena observed in the very high state and possibly also the apparent decoupling of hard X-ray flux from the mass accretion rate.

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