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Evidence for two-component flows around the black hole candidate XTE J1550−564 from spectral features during its 1998–1999 outburst

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ABSTRACT

We study the spectral properties of the accretion disc in the Galactic black hole candidate XTE J1550−564 during the 1998–1999 outburst when the source exhibited double-peaked eruptions. This outburst lasted for 250 d and the 2.5–25.0 keV spectral state varied smoothly from one to another several times. We show that the spectral features of the 1998–1999 outburst could be clearly understood by a two-component (Keplerian and sub-Keplerian) advective flow (TCAF). We concentrate on the spectral data from a Proportional Counter Array instrument on the *RXTE* satellite for the black hole XTE J1550−564 and fit them quite satisfactorily using TCAF model. From the spectral fit we calculate the disc parameters, such as the Keplerian rate, the sub-Keplerian rate (halo rate), the shock location and the inner edge of the Keplerian disc. This observation points to the presence of two independent components in the accretion flow and that the accretion rate at all radii need not be constant in an evolving disc.

Key words: accretion, accretion discs – black hole physics – shock waves – stars: individual: XTE J1550−564.

1 INTRODUCTION

The black hole candidate and the X-ray nova XTE J1550−564 was discovered by the All-Sky Monitor (ASM) on board the *Rossi X-Ray Timing Explorer* (*RXTE*) on 1998 September 7 (MJD 51063) (Smith 1998) and also by the Burst and Transient Source Experiment (BATSE) on board *Compton Gamma Ray Observatory* (*CGRO*; Wilson et al. 1998). The optical (Orosz, Bailyn & Jain 1998) and the radio (Campbell-Wilson et al. 1998) counterparts were detected shortly afterward. From subsequent observations it is established that the black hole in XTE J1550−564 has a mass of $10.0 \pm 1.5\,M_\odot$ (Orosz et al. 2002). The companion is a late-type subgiant (G8IV–K4III) star and the binary inclination angle is $72^\circ \pm 5^\circ$ (Orosz et al. 2002).

The profile of the entire 1998–1999 outburst of the black hole candidate XTE J1550−564 can be understood from the light curve of ASM. The whole outburst eruption was a 'double-peaked' profile where the first half is dominated by the power-law emission and the second half is dominated by the soft emission from the Keplerian disc. This outburst behaviour is similar to the outburst behaviour of GRO J1655−40 during 1996 (Sobczak et al. 2000a) and 2005 (Chakrabarti et al. 2005, 2008; Shaposhnikov et al. 2007). A total of 209 pointed observations using Proportional Counter Array (PCA) and High Energy X-ray Timing Experiment (HEXTE) instruments on board the *RXTE* spanning 250 d covered the entire outburst of 1998–1999. The detailed fit of the spectra to a specific model including multicolour blackbody disc and power-law component was done by Sobczak et al. (2000a,b). During the onset phase (MJD 51063–51072), the photon index gradually steepens from $\Gamma = 1.5$ to 2.5, the spectrum is strongly dominated by a power-law emission and the source displays a strong quasi-periodic oscillation (QPO) in the 0.08–8 Hz range (Cui et al. 1999). A high energy cut-off is observed in the HEXTE spectrum during the initial rise. The spectra from MJD 51074 to MJD 51115 was found to be dominated by a power-law component with the photon index $\Gamma \sim$ 2.4–2.9. The source displays a strong 3–13 Hz QPO during this time and the power law contributes 60 per cent of the observed X-ray flux (Remillard et al. 1999; Sobczak et al. 2000b). This spectral feature is consistent with a *'very high state'* of black hole X-ray novae and the inner disc radius is observed to vary as well. This radius is decreased by a factor of 16 on MJD 51075.99 (day of flare) when the smallest radius was observed. The power-law component started decaying from MJD 51115 and the source intensity also decayed exponentially till MJD 510150. The power-law photon index γ hardens and is around 2.0–2.4. At the same time, the flux from the disc component begins to dominate in the spectrum. This state is termed as the *intermediate state* (Sobczak et al. 2000a,b) and no regular QPO is observed but the source occasionally exhibits QPOs at ∼5 Hz. After this *very high state/intermediate state*, the intensity increases sharply after MJD 51150 making a start of the second phase (MJD 51150–51311) of the outburst. During this phase, the

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observed spectra are dominated by the disc component (contributing 85 per cent of the 2–20 keV flux). In this case also no QPOs were found. The power-law flux increases after MJD 51230 and an intense power-law flare starts on the MJD 51241 and lasts up to MJD 51260 accompanied by a fast decrease in the disc flux. The total flux (dominated mainly by the power law) decreases exponentially from MJD 51260 till the end of the outburst (MJD 51311). In the last few observations, the source was seen to go to the *low/hard* state.

So far, no study has been made as regard to the actual nature of what really goes on physically during an outburst. To understand the physical nature of the accretion flow during this exciting evolution of the spectrum it is important to analyse it keeping a physical model in mind and try to see if the model remains consistent for the entire evolution. The recent observed timing and spectral properties of several Galactic black holes indicated that the accretion flows around a black hole may have two components (Chakrabarti 1997, hereafter C97; Smith et al. 2001; Smith, Heindl & Swank 2002; Choudhury & Rao 2004; Pottschmidt et al. 2006; Smith, Dawson & Swank 2007; Chakrabarti et al. 2008; Debnath et al. 2008; Chakrabarti, Dutta & Pal 2009): one is an optically thick but geometrically thin Keplerian accretion disc (Shakura & Sunyaev 1973) on the equatorial plane and the other is an optically thin sub-Keplerian flow (Chakrabarti 1989; Chakrabarti & Titarchuk 1995, hereafter CT95) which surrounds the Keplerian disc. The Keplerian disc itself produces a multicolour blackbody spectrum. The soft photons from the Keplerian disc are inverse Comptonized by the hot electron cloud produced due to a shock transition in presence of the centrifugal force in the sub-Keplerian flow. This is known as the CENtrifugal pressure supported BOundary Layer (CENBOL) of the black hole. The CENBOL is responsible for producing the high-energy spectrum out of an accretion disc. This two-component nature of the disc can be treated as a general model where the accretion rates of both the components can be varied independently. The jets and outflows formed out of the CENBOL region and may also contribute to some of the X-rays. Sometimes the CENBOL may itself be included in side the jet and then the entire X-ray could come out of the jet itself (Körding, Fender & Migliari 2006). There are several other models in the literature which also address the change in spectral states by changing various components of the model (Haardt & Maraschi 1991; Wandel & Liang 1991; Esin, McClintock & Narayan 1997; Janiuk & Czerny 2000; Merloni & Fabian 2001; Zdziarski et al. 2003). An important difference between these models and the current model used is that in CT95 and C97 both the components are *dynamic* rather than static, i.e. accreting. Specifically, the Comptonized cloud or CENBOL, arises out of the sub-Keplerian flow. However, none of these models seems to satisfactorily unify the entire variation that is observed in an outburst source (see e.g. McClintock & Remillard 2006 for details).

In the literature, a significant number of works in the analysis and interpretation of the spectral and timing properties of XTE J1550−564 during its outbursts have been reported. Soria et al. (2001) and Wu et al. (2002) showed that during the same outburst, the hard X-ray flux from BATSE (in the 20–200 keV range) reached its maximum after 1 d, and started to decline in the next 3–4 d, though the soft X-ray flux from *RXTE*/ASM (2–12 keV) continued to rise monotonically for 10 d or so. Subsequently, both the hard and the soft X-ray bands flared after 12 d of the initial hard X-ray spike. This sequence of behaviours leads to the conclusion that the Keplerian disc is not enough to explain the observations and both the low and the high angular momentum flows could be present simultaneously as described in CT95. Reilly et al. (2001), using the result from Unconventional Stellar Aspect (USA) experiment on board the *Advanced Research and Global Observations Satellite* (*ARGOS*), showed that the centroid frequency of low-frequency QPOs during the 2000 outburst of XTE J1550−564 tends to rise with the increasing USA flux in 1–16 keV. They study the correlations of the hard and soft fluxes and concluded that the observations could be explained only if the flow has two independent components, one Keplerian and the other sub-Keplerian. Sobczak et al. (2000a,b) reported similarities and differences between the two outburst sources, namely, GRO J1655−40 and XTE 1550−564. They find that both exhibited a general increase in QPO frequency with the disc flux. QPOs are found to be present only when the power-law component contributes more than 20 per cent of the 2–20 keV flux, thus agreeing with the general perception that only the Comptonized photons take part in QPOs (Chakrabarti & Manickam 2000; Rao et al. 2000). More recently, Chakrabarti et al. (2009) have shown that the evolution of QPO frequency during the onset of 1998–1999 outburst for this object can be satisfactorily explained by the propagatory and oscillatory shock model which requires two independent components.

The plan of the paper is the following: In the next section, we discuss the two-component advective flow (TCAF) model and possible spectral features. In Section 3, we present the PCA spectral data for 1998–1999 outburst and superposed on them the spectra obtained from the TCAF model. The fits are found to be satisfactory for all the spectral states. From the fitting, we calculate the disc rate, halo rate, the location of the inner disc radius and the locations of the shock (CENBOL region). Finally, in Section 4, we present our concluding remarks as to what these results tell us about the nature of the accretion process in this object.

2 SPECTRAL PROPERTIES OF TWO-COMPONENT FLOW AND THE PHYSICAL PROCESSES

A detailed description of the two-component model has been given in CT95 and C97 and this will not be repeated here. In the so-called TCAF, instead of viscosity and Keplerian disc rate as free parameters, the rates of the Keplerian disc ($\dot{m}_\mathrm{d}$) and the sub-Keplerian halo ($\dot{m}_\mathrm{h}$) components are assumed as free parameters. Both the components are assumed to be present in the inner region of the disc, though, with the variation of viscosity, the sub-Keplerian component may be converted to the Keplerian component and vice versa. In any case, close to the black hole, both the components must become sub-Keplerian to comply with transonicity condition near the horizon. The black hole geometry is described by a pseudo-Newtonian potential (Paczyński & Wiita 1980) and the vertical height of the disc at any radial distance is calculated by balancing the vertical component of gravitational force with the gas pressure (Chakrabarti 1989). This assumption may not be valid very close to the horizon where the flow is highly supersonic (this region contributes insignificant number of photons in the outgoing spectrum, anyway), but in the CENBOL, i.e. the post-shock region, the assumption is valid (Giri et al. 2010), since the flow is subsonic and has time to expand vertically. The radial distance is measured in units of Schwarzschild radius (r_g). The parameters of our model are the shock location (r_s), the compression ratio (R, which is the ratio of the post-shock to pre-shock densities) and the accretion rates of the Keplerian ($\dot{m}_\mathrm{d}$) and the sub-Keplerian halo ($\dot{m}_\mathrm{h}$) components. These accretion rates are measured in units of the Eddington rate. In our model, we consider only bremsstrahlung and Compton scattering as the main radiative processes. The effects of synchrotron radiation and bulk motion Comptonization has been taken care of by adding a weak power-law component, especially in the hard states.

3 OBSERVATION AND DATA ANALYSIS

In this paper, we fit the data of 26 observational IDs (which span a total of 250 d) of XTE J1550−564 due to *RXTE* PCA (Jahoda et al. 1996). We used the best calibrated PCA detector unit, namely, PCU2. We used FTOOLS software package version 6.1.1 and XSPEC version 12.3.0.

The ASM light curve (Fig. 1) shows the transition from the first phase (when the spectrum is power law dominated) to the second phase (when the spectrum is disc dominated) and finally from the second phase to the quiescent state. In the last phase, the overall source flux decreases exponentially (Soria et al. 2001; Wu et al. 2002) with identical time-scale of ∼11 d. We shall analyse these phases below.

Table 1 shows the fitted parameters from the two-component flow model for the first few days of data where two variations of the model (Model I of CT95 and Model II of C97, respectively) are presented. In Model I, the inner ($r_{K,i}$) and the outer ($r_{K,o}$) edges of the Keplerian disc were assumed to be fixed at $8r_s$ and $300r_s$, respectively, as in the CT95 model. The disc and the halo rates in the units of the Eddington rate are given. To fit the iron line we added a Gaussian component whose peak ($E_{\rm line}$) and width ($L_{\rm width}$) are also given in Table 1. Table 2 that shows the fitted parameters for the remaining days uses Model I but the iron line was absent. Instead, a weak power-law component of spectral slope of $-\Gamma$ and its normalization factor $P_{\rm norm}$ (with respect to the intensity of the power law due to Comptonization) added to obtain a better fit. The overall normalization factor is 36.25 in log scale and is constant throughout. This constant brings the theoretically computed value on the observational data and its constancy throughout the entire period implies that our analysis is self-consistent. The shock location is the same as the inner edge of the Keplerian disc (CT95). In the last two columns, we present χ^2/ν from two models, where ν is the number of degrees of freedom to show that the fits are generally acceptable.

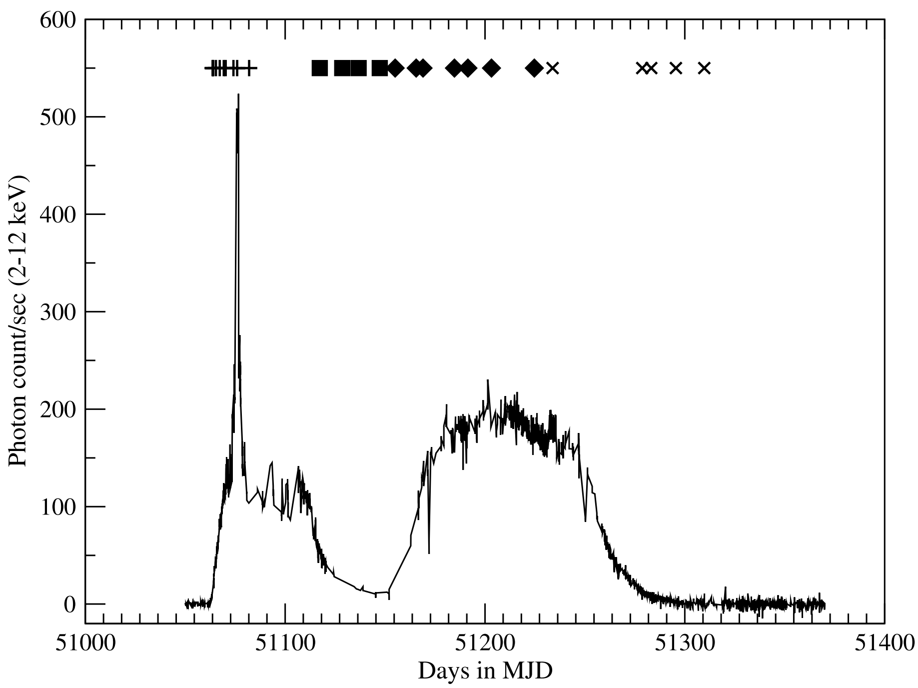

Figure 1. The 2–12 keV ASM light curve for XTE J1550−564. The markers at the top of the diagram indicate dates on which the spectra were examined with the two-component model. The ‘plus’ sign represents the hard state, the ‘rectangular’ sign represents ‘very high/intermediate state’, the ‘diamond’ sign represents the ‘soft state’ and ‘cross’ sign represents ‘low/intermediate state’.

Table 1. Estimated disc parameters in the first phase of the outburst with two TCAF models.

MJD	$\dot{m}_h$		$\dot{m}_d$		$(r_{K,i})$		r_s		$E_{\rm line}$	$L_{\rm width}$	χ^2/ν	
	I	II	I	II	I	II	I	II	(keV)	(keV)	I	II
51063.7037	0.302	0.02425	0.31	8.649	8	85	8	67	6.45	0.6	70.1(39)	37.9(39)
51064.0068	0.312	0.02825	0.40	6.709	8	85	8	67	6.45	0.6	54.2(39)	45.7(39)
51065.3420	0.390	–	1.08	–	8	–	8	–	6.50	0.65	57.7(39)	–
51067.2710	0.280	0.07665	1.52	4.239	8	75	8	54	6.40	0.6	58.0(39)	32.5(39)
51069.2817	0.390	–	3.82	–	8	–	8	–	6.40	0.6	53.1(39)	–
51070.2740	0.390	–	3.72	–	8	–	8	–	6.55	0.8	41.2(39)	–
51074.1400	0.255	–	2.76	–	8	–	8	–	6.55	0.8	31.2(39)	–
51075.9900	0.508	–	11.80	–	8	–	8	–	6.40	1.1	48.0(39)	–
51082.0020	0.384	0.24200	3.41	12.000	8	74	8	54	6.55	1.1	58.2(39)	20.9(39)

Table 2. Estimated disc parameters of using Model I of TCAF.

MJD	$\dot{m}_h$	$\dot{m}_d$	Γ	P_{norm}	χ^2/ν
51117.351	0.440	5.20	1.32	0.008	50.2/(39)
51128.564	0.310	3.00	1.40	0.007	50.5/(39)
51136.777	0.190	2.00	1.49	0.004	53.4/(35)
51147.335	0.460	4.15	1.42	0.002	55.7/(33)
51155.067	0.155	8.15	1.40	0.004	50.2/(35)
51165.590	0.160	8.05	–	–	53.4/(34)
51169.009	0.170	9.95	–	–	51.1/(35)
51184.711	0.180	12.25	1.51	0.0004	49.3/(38)
51191.485	0.150	12.25	–	–	50.3/(40)
51203.249	0.230	12.65	–	–	31.0/(38)
51224.699	0.180	11.45	1.51	0.0003	41.4/(35)
51233.835	0.580	11.45	1.35	0.010	53.1/(37)
51278.686	0.230	2.05	1.30	0.005	58.1/(36)
51283.224	0.170	1.30	1.49	0.002	35.4/(24)
51295.520	0.160	0.56	1.40	0.0004	6.7/(7)
51309.720	0.250	0.336	–	–	8.1/(7)

While Model I would have been sufficient to explain the entire spectral evolution, we decided to fit with a totally different model (Model II) proposed by C97. Here, we use a truncated disc on certain days with the outer radius still located at 300 r_s, while the inner radius was varied (Table 1). Here the fits are better (see the χ^2 in the last columns). The normalization factor of 34.25 in log scale was chosen for these days. This separate normalization is required as the model itself is different. It is possible that the disc is not in equilibrium during the evolution, since the Keplerian disc would evolve in ∼10–12 d while the sub-Keplerian component evolves faster (less than a day). Thus, fitting a spectrum with a constant accretion rate at all radii may not be accurate. On the other hand, a better fit with a truncated disc model indicates that the inner edge of the Keplerian disc indeed moves in during the rising phase.

Fig. 2 shows the variations of the accretion rates of the two components which are needed to fit the spectra during the whole outburst. The rates are taken from Tables 1 and 2. Only Model I results were used. Given that both the components are fitting the spectra, a variation of the Keplerian accretion rate with that of the light curve (Fig. 1) is very striking. We note that the halo rate changes only by a factor of 4 during the outburst, but the Keplerian rate changes more significantly, almost 40 times. However, since the efficiency of Keplerian accretion in a Schwarzschild black hole is at the most 6 per cent, the total luminosity still remains sub-Eddington.

Fig. 3 depicts the fitted whole spectra during the outburst put together. Here, for simplicity, we used only two components without the iron line or extra power law due to synchrotron radiation or bulk motion Comptonization. We plot $E^2 I(E)$ to show that spectra actually belong to three distinct categories, which are low/hard state (LHS) having slopes close to ∼1.5, very high/intermediate state (VHIS) having slopes close to ∼2.0 and soft/high state (SHS) having slopes close to ∼2.5. The outburst started with a low/hard state and after passing through the so-called very high/intermediate state and soft state, it reverted back to the low/hard state towards the end which lasted for a few days.

In Fig. 4, we present the PCA spectral data of *RXTE* from 2.5 to 20.0 keV energy range with TCAF model (Model I). A few days of data from the initial hard state are plotted by solid circles. Solid curves represent spectra using our best guess of accretion rates and Gaussian curve parameters for the Fe lines (Table 1). In Fig. 5, we similarly present the guess of the flow rate parameters using Model II, where the inner edge of the Keplerian disc and the shock locations were varied (Table 1). The data are reduced by using the interstellar Wisconsin absorption model (Morrison & McCammon 1983). For all the observations in this paper, we fixed the hydrogen column density to be N_H at 2.0×10^{22}. In Model II, during the onset of the outburst, the Keplerian disc was far away from the source and as the day progresses the disc moved towards the source. The shock was also located far away from the source and proceeded

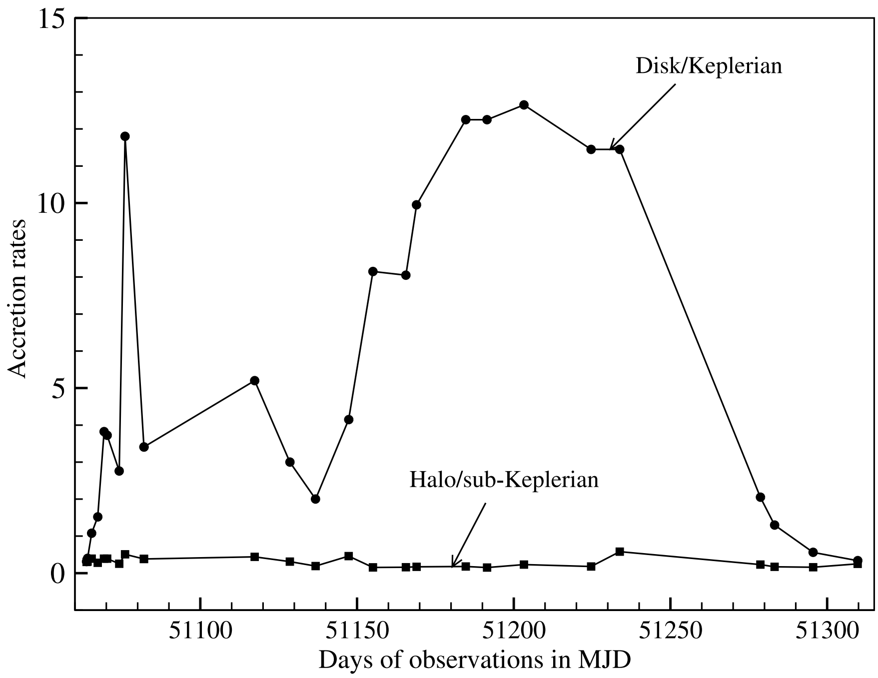

Figure 2. The variation of the disc and the halo accretion rates with the day (MJD). We plot the disc/Keplerian accretion rate and halo/sub-Keplerian accretion rate using the fitted parameters from Tables 1 and 2.

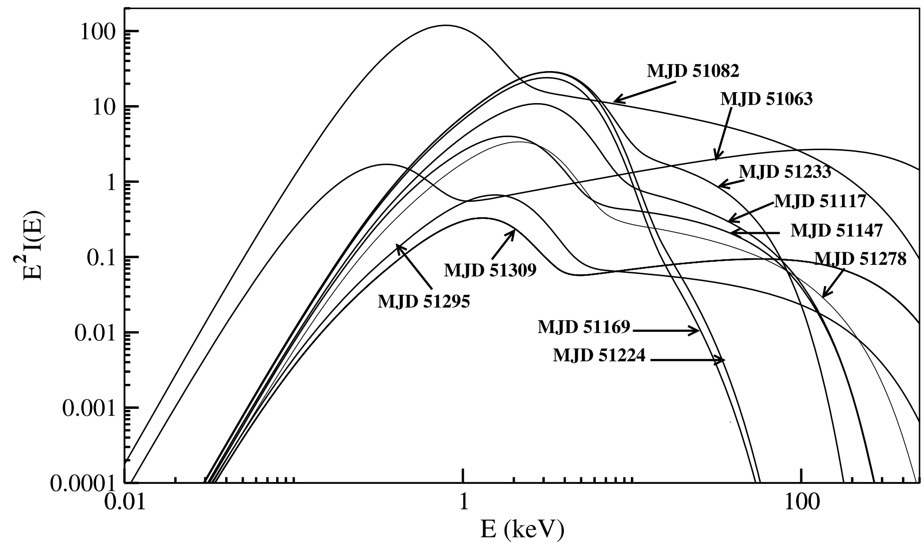

Figure 3. The fitted powers using the two-component advective disc model for the whole outburst are plotted. We plot $E^2 I(E)$ versus energy (keV). The fitted curves could be divided into three distinct spectral states, i.e. LHS, having slopes close to ∼1.5, VHIS, having slopes close to ∼2.0 and SHS, having slopes close to ∼2.5 were observed. The outburst followed the sequence of LHS, VHIS, SHS and reverting back to LHS for a few days at the end.

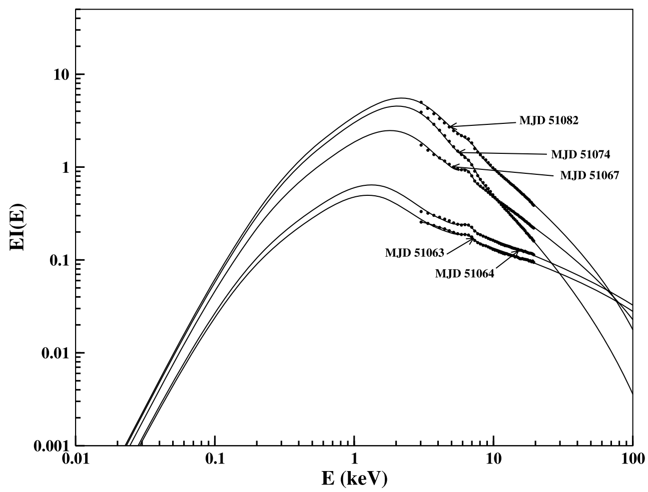

Figure 4. Spectral data (solid circles) in the hard state to intermediate state (MJD 51063 to MJD 51083). The accretion rates of the disc and the halo components are estimated from Model I and spectra drawn are superposed by solid curves. A constant CENBOL size was used. The iron line was fitted with a Gaussian component (Table 1).

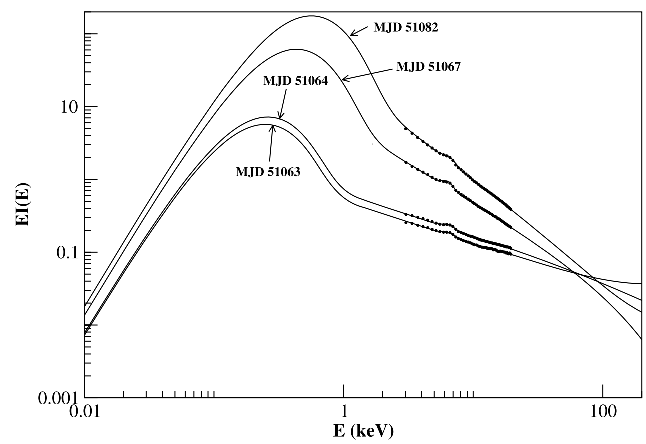

Figure 5. Spectral data (solid circles) in the hard state to intermediate state (MJD 51063 to MJD 51082). The accretion rates of the disc and the halo components are estimated (Table 1) from Model II and the corresponding spectra are superposed by solid curves. The location of the shock ($r_{\rm s}$) and the inner edge of the Keplerian disc ($r_{\rm K,i}$) are also chosen as variables in this case (Table 1). The iron line was fitted with a Gaussian component (Table 1).

towards the black hole gradually. This implies that the size of the CENBOL was initially larger and is responsible for the initial hard state. Notice that the reduced χ^2 is lower with Model II parameters whenever the fits were possible. This means that the Keplerian disc is indeed moving in the rising phase.

In Figs 6(a)–(d), we present spectra (solid circles) of different days of the outburst and the solid lines represent the computed spectra using our best guess of disc parameters and Model I. We used a broad absorption line on MJD 51147 and on MJD 51136 near 10.5 keV for a realistic fit. We have used a weak power law characterized by the slope $-\Gamma$ and the normalization $P_{\rm norm}$ to get a better fit. $P_{\rm norm}$ is the fraction of the added power-law energy and the power law due to thermal Comptonization. This type of power laws have been invoked before while fitting the spectra to very high energies (Wardzinski & Zdziarski 2001; Chakrabarti & Mandal 2006; Niedwiecki & Zdziarski 2006) and could be due to Comptonization of the non-thermal photons generated by the non-thermal electrons from shock acceleration. The days in MJD are marked as before. The comparison of the spectra shows the typical signatures of two-component flows. For instance, in Fig. 6(a), generally, both the soft and hard powers are lower. However, on MJD 51147, the power-law spectrum extended till higher energy, though at lower energy the power is similar to that on MJD 51136. In Figs 6(b) and (d), there is a general tendency of the power to fall gradually at all wavelengths indicating that both components are decreasing as the time progressed. In Fig. 6(c), the soft photon energy is similar, but there is a major change in the hard X-ray content in the power indicating that the Keplerian rate remains nearly constant while the fractional change in the sub-Keplerian halo is large. As on some days before, we used an absorption line near 10 keV on MJD 51283 and on MJD 51278 in order to make the fit better.

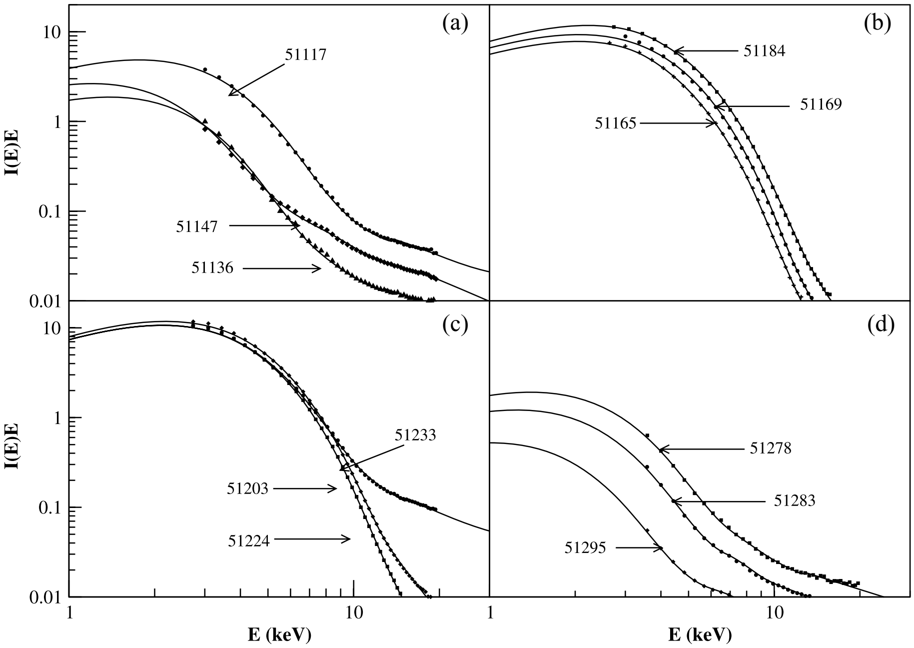

Figure 6. Spectral data (solid circles) during the very high/intermediate state, transition to soft/high state and again transition to intermediate state. Superposed in solid curves are the spectra from Model I using estimated accretion rates (Table 2) in two components. The days in MJD are marked.

4 DISCUSSIONS AND CONCLUDING REMARKS

After carefully analysing the spectral data during the outburst of XTE J1550−564, we discover several exciting facts about this object. First of all, we find that one cannot fit the spectral data using only a single component of accretion disc. Several attempts were made with a single component, by varying a truncated Keplerian disc only, and also using discs with different radial dependence of the temperature profile as in Shakura & Sunyaev (1973), but all such attempts were failed. If we use two components with varying rates (Fig. 2) and use the Keplerian disc with a fixed inner edge as in CT95, a satisfactory fit is possible (Fig. 5) throughout the outburst. Occasionally, especially in the rising phase, a better fit was obtained by varying the shock location and the inner edge of the Keplerian disc (Table 1) as suggested in CT97. Of course, this different model required a different normalization constant, as expected.

In the present paper, we analysed the results only up to ∼20 keV because we were interested to show that two components are essential. At the same time, we find indications that a power-law component above ∼10 keV was essential in second part of the outburst (Table 2) in order to have a better fit. Because these are required in hard states only, they may be due to the non-thermal photons generated from non-thermal electrons. Earlier it was indicated the contribution of the non-thermal power law in Cyg X-1 is less than a few per cent (Wardzinski & Zdziarski 2001; Chakrabarti & Mandal 2006; Niedwiecki & Zdziarski 2006). Indeed, we also find that its contribution here is less than 1 per cent.

The cause of the difficulty of fitting the data over the entire range using one single model yielding very good χ^2 is worth investigating, and perhaps this means that we are seeing the effects of a disc which in essentially not in equilibrium. It is well known that a Keplerian disc flows in viscous time-scales, and thus requires a longer time to move towards the black hole, while the sub-Keplerian halo moves roughly in the free-fall time-scale (CT95). This has been found to be the case while explaining the timing properties of several black hole candidates (e.g. Smith et al. 2001, 2002) where it was found that the viscous time-scale of a few days was responsible to explain the lag between the change in the spectral index and the intensity of soft photons. In the present case the situation is more complex, since it is an outburst source and thus has an accretion rate which is variable *both in time and in space*. It is unlikely that steady solutions of Keplerian and sub-Keplerian flows can be justifiably used at any given moment. For the sake of argument, if we consider ∼11 d to be the viscous time-scale required to drain the matter from the disc (Soria et al. 2001; Wu et al. 2002) in this object, one may assume that the Keplerian disc must have started moving in almost from day 1 (MJD 51063.7) so that on ∼MJD 51075 the Keplerian rate is maximum. This is consistent with what we found. However, this does not imply that the same highest $M_{\rm d}$ was prevalent *everywhere* in the disc! Thus the disc modelling is to be carried out with time and distance dependence of the rates, consistent with the time lag due to viscous time-scale. An additional complication arises because winds and outflows may be formed from the CENBOL, i.e. the Comptonizing cloud itself. On MJD 51074, we notice that the spectrum suddenly softens, which is a direct indication of the removal of matter from the CENBOL (Chakrabarti 1999). Indeed a recent paper by Hannikainen et al. (2009) shows direct evidence of superluminal ejection during this period. The entire scenario is thus intrinsically time dependent and fitting spectra using steady state model could create confusion. The solution is perhaps best obtained by computing time-dependent simulations of the outburst sources which will be reported elsewhere.

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REFERENCES

Campbell-Wilson D., McIntyre V., Hunstead R. W., Green A., 1998, Int. Astron. Union Circular, 7010, 3
Chakrabarti S. K., 1989, ApJ, 347, 365
Chakrabarti S. K., 1997, ApJ, 484, 313 (C97)
Chakrabarti S. K., 1999, Indian J. Phys., 72B, 565
Chakrabarti S. K., Mandal S., 2006, ApJ, 642, L49
Chakrabarti S. K., Manickam S. G., 2000, ApJ, 531, L41
Chakrabarti S. K., Titarchuk L. G., 1995, ApJ, 455, 623 (CT95)
Chakrabarti S. K., Nandi A., Debnath D., Sarkar R., Dutta B. G., 2005, Indian J. Phys., 78B, 1
Chakrabarti S. K., Debnath D., Nandi A., Pal P. S., 2008, A&A, 489, L41
Chakrabarti S. K., Dutta B. G., Pal P. S., 2009, MNRAS, 394, 1463
Choudhury M., Rao A. R., 2004, ApJ, 616, L143
Cui W., Zhang S.-N., Chen W., Morgan E. H., 1999, ApJ, 512, L43
Debnath D., Chakrabarti S. K., Nandi A., Mandal S., 2008, Bull. Astron. Soc. India, 36, 151
Esin A. A., McClintock J. E., Narayan R., 1997, ApJ, 489, 865
Giri K., Chakrabarti S. K., Samanta M. M., Ryu D., 2010, MNRAS, in press (arXiv:0912.1174)
Haardt F., Maraschi L., 1991, ApJ, 380, L51
Hannikainen D. C. et al., 2009, MNRAS, 397, 569
Jahoda K., Swank J. H., Giles A. B., Stark M. J., Strohmayer T., Zhang W., Morgan E. H., 1996, Proc. SPIE, 2808, 59
Janiuk A., Czerny B., 2000, New Astron., 5, 7
Körding E. G., Fender R. P., Migliari S., 2006, MNRAS, 369, 1451
McClintock J. E., Remillard R. A., 2006, in Lewin W., van der Klis M., eds, Compact Stellar X-Ray Sources. Cambridge Univ. Press, Cambridge, p. 157
Merloni A., Fabian A. C., 2001, MNRAS, 321, 549
Morrison R., McCammon D., 1983, ApJ, 270, 119
Niedwiecki A., Zdziarski A. A., 2006, MNRAS, 365, 606
Orosz J. A., Bailyn C. D., Jain R. K., 1998, Int. Astron. Union Circular, 7009, 1
Orosz J. A. et al., 2002, ApJ, 568, 845
Paczyński B., Wiita P. J., 1980, A&A, 88, 23
Pottschmidt K., Chernyakova M., Zdziarski A. A., Lubiński P., Smith D. M., Bezayiff N., 2006, A&A, 452, 285
Rao A. R., Naik S., Vadawale S. V., Chakrabarti S. K., 2000, ApJ, 360, 25
Reilly K. T. et al., 2001, ApJ, 561, L183
Remillard R. A., McClintock J. E., Sobczak G. J., Bailyn C. D., Orosz J. A., Morgan E. H., Levine A. M., 1999, ApJ, 127, L517
Shakura N. I., Sunyaev R. A., 1973, A&A, 24, 33
Shaposhnikov N., Swank J., Shrader C. R., Rupen M., Beckmann V., Markwardt C. B., Smith D. A., 2007, ApJ, 655, 434
Smith D. M., 1998, Int. Astron. Union Circular, 7008, 1
Smith D. M., Heindl W. A., Markwardt C. B., Swank J. H., 2001, ApJ, 554, L41
Smith D., Heindl W. A., Swank J. H., 2002, ApJ, 569, 362
Smith D. M., Dawson D. M., Swank J. H., 2007, ApJ, 669, 1138
Sobczak G. J., McClintock J. E., Remillard R. A., Cui W., Levine A. M., Morgan E. H., Orosz J. A., Bailyn C. D., 2000a, ApJ, 531, 537
Sobczak G. J., McClintock J. E., Remillard R. A., Cui W., Levine A. M., Morgan E. H., Orosz J. A., Bailyn C. D., 2000b, ApJ, 544, 993
Soria R., Wu K., Hannikainen D., McMollough M., Hunstead R., 2001, in Yaqoob T., Krolik J. H., eds, Proc. Joint Workshop on X-Ray Emission from Accretion on to Black Holes. NASA/GSFC, Maryland, p. 65
Wandel A., Liang E. P., 1991, ApJ, 380, 84
Wardzinski G., Zdziarski A. A., 2001, MNRAS, 325, 963
Wilson C. A., Harmon B. A., Paciesas W. S., McCollough M. L., 1998, Int. Astron. Union Circular, 7010, 2
Wu K. et al., 2002, ApJ, 565, 1161
Zdziarski A. A., Lubinski P., Gilfanov M., Revnivtsev M., 2003, MNRAS, 342, 355

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