SPECTRAL EVOLUTION OF THE CONTINUUM AND DISC LINE IN DIPPING IN GRO J1655-40

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ABSTRACT

The discovery is reported of emission features in the X-ray spectrum of GRO J1655-40 obtained using Rossi-
XTE on 1997, Feb 26. The features have been fitted firstly by two Gaussian lines, which in four spectra have average energies of 5.85 ± 0.08 keV and 7.32 ± 0.13 keV, strongly suggestive that these are the red and blue shifted wings of an iron disc line from material with velocity ∼0.33 c. The blue wing is apparently less bright than expected for a disc line subject to Doppler boosting, however, known absorption in the spectrum of GRO J1655-40 at energies between ∼7 and 8 keV can reduce the apparent brightness of the blue wing. The spectra have also been fitted well using the full relativistic disc line model of Laor, plus an absorption line. This gives a restframe energy between 6.4 and 6.8 keV indicating that the line is from highly ionized iron Kα. The Laor model also shows that the line originates at radii extending from ∼10 Schwarzschild radii (rS) outwards. The line is direct evidence for the black hole nature of the compact object. The continuum is well described by dominant disc blackbody emission plus Comptonized emission. During dipping, spectral evolution is well modelled by allowing progressive covering of the disc blackbody and simple absorption of the Comptonized emission showing that the thermal emission is more extended. Acceptable fits are only obtained by including the disc line in the covering term, indicating that it originates in the same inner disc region as the thermal continuum. Dip ingress times and durations are used to provide the radius of the disc blackbody emitter as 170–370 rS, and the radius of the absorber.

INTRODUCTION

GRO J1655-40 (X-ray transient Nova Sco 1994) is a Galactic Jet Source first discovered in hard X-rays with BATSE (Zhang et al. 1994). It underwent several X-ray outbursts between July 1994 until September 1997 when the source switched off in X-rays. High resolution radio observations revealed apparently superluminal, relativistic jets moving in opposite directions with velocity of 0.92 c (Hjellming & Rupen 1995, Tingay et al. 1995). However, radio activity of the source is apparently not correlated with X-ray outbursts. The source was active at radio wavelengths only for approximately 6 months during the early stage of X-ray activity in 1994 (Hjellming & Rupen 1995). Shahbaz et al. (1999) used optical observations to obtain a well-constrained mass range for the compact object of 5.5–7.9 M⊙, leaving no doubt that this is a black hole. The inclination of the system is in the range of 63.7–70.7° (van der Hooft et al. 1998). The black hole is surrounded by a massive accretion disc filling approximately 85% of the Roche lobe radius (Orosz & Bailyn 1997).

The source shows strong X-ray dipping, i.e. reductions of X-ray intensity caused by obscuration of the X-ray source by absorbing material in the line of sight (Fig. 1, left). The dipping provides a diagnostic of the X-ray emission regions and strongly constrains spectral models because of the requirement that emission models fit several dip spectra as well as non-dip. It occurs in this source predominantly in orbital phase 0.68–0.92 (Kuulkers et al. 2000) suggesting that blobs of absorbing material are located most probably on the outer rim of the accretion disc as in LMXB.

Recently, a highly red- and blue-shifted iron disc line has been discovered in the X-ray spectrum of GRO J1655-40 (Bahucińska-Church & Church 2000) from the observation with Rossi-XTE on 26th February,
1997. The observation took place at the beginning of the last outburst seen before the complete switch-off in X-rays. The source has not been detected in radio since 1996 despite regular monitoring (Tingay, priv. comm.). During this observation, strong X-ray dipping occurred. In the present paper I will discuss the evolution of the continuum and the iron disc line during dipping using this data, and will also show how the X-ray dipping constrains emission region sizes.

**THE PERSISTENT EMISSION SPECTRUM: DETECTION OF THE DISC LINE**

The observation of GRO J1655-40 discussed in this paper was made on 1997, February 26, lasting 14,600 s with an on-source good exposure time of 7,600 s. Data from the Proportional Counter Array (PCA) instruments are presented. Four spectra during persistent emission were carefully selected from regions of the lightcurve where the count rate was particularly stable. The spectra were fitted with a model consisting of a disc blackbody and a power law. The same model was also used by Zhang et al. (1997). The disc blackbody having temperature \( kT \sim 1.1 \text{ keV} \) was the dominant component contributing 90% to the total luminosity (0.1–100 keV) of \( 9.6 \times 10^{37} \text{ erg s}^{-1} \) which is \( \sim 10\% \) of the Eddington luminosity for a 7\( M_\odot \) object. The power law was very steep with the photon index \( \Gamma \sim 2.4 \). The continuum parameters agree well with the results published by Kuulkers et al. (1998). Although the above model gave the best fit to the continuum, the fits were generally poor (\( \chi^2/\text{dof} \sim 133/91 \)) with systematic residuals at \( \sim 5.8 \text{ keV} \) and \( \sim 7.3 \text{ keV} \) in every spectrum analysed (Fig. 1, right).

By adding two Gaussian lines to the continuum, the fits became very good with \( \chi^2/\text{dof} \sim 70/85 \), and an F-test showed that the fits were improved with significance >> 99.9% (Fig. 2, left). The mean line energies of the four spectra are \( \bar{E}_1 = 5.85 \pm 0.08 \) and \( \bar{E}_2 = 7.32 \pm 0.13 \text{ keV} \). If we assume that the splitting of the two lines is caused by the relativistic Doppler shift, the rest energy of the line is \( E_{\text{rest}} = 6.88 \pm 0.12 \text{ keV} \) and the velocity \( v/c = \beta \) is 0.33 for an inclination \( \dot{i} = 70^\circ \). However, the intensity of the “blue” line is always smaller than the intensity of the “red” line. Therefore, the intensities of the two lines observed cannot simply be due to a disc line where Doppler boosting of the blue line is expected. However, in several ASCA spectra of GRO J1655-40 iron absorption-line features were found at energies which will influence the observed strength of the blue line (Ueda et al. 1998).

Consequently, we carried out spectral fitting with the continuum described as before and a Laor disc line + an absorption line added. Good quality fits (\( \chi^2/\text{dof} \sim 76/84 \)) were obtained for all spectra with results as follows. The mean value of rest-frame energy of the emission line was \( 6.56 \pm 0.14 \text{ keV} \) corresponding to
highly ionized Fe (XXII) Kα emission. However, the energy varied from 6.4 keV to 6.8 keV between spectra not constraining very well the ionization state. The inner radius of the emission region \( r_1 \) was found to be \( \sim 10 \, r_S \) where \( r_S \) is the Schwarzschild radius (19.9 ± 3.6 km for the possible range of black hole mass in this source); the outer radius \( r_2 \) was poorly constrained to \( \geq 50 \, r_S \). The inner radius value being larger than the radius of the last stable orbit suggests that the inner part of the disc up to 10 \( r_S \) is totally ionized and does not contribute to the emission line. The mean energy of the absorption line from the 4 spectra is well constrained at 7.09 ± 0.13 keV corresponding to the Fe Kα or Fe Kβ line and occurs at the same energy as the blue wing of the disc line. Thus it is quite possible to fit the observed features by a combination of a Laor disc line with absorption (known to take place in the source), and the emission line has the expected profile with a boosted blue wing (Fig. 2, right). Iron disc lines have since been detected in 4U 1630-47 (Cui et al. 2000) and XTE J1748-288 (Miller et al. 2000).

**SPECTRAL EVOLUTION IN DIPPING: THE LINE AND CONTINUUM**

During the Rossi-XTE observation, strong X-ray dipping took place (see also Kuulkers et al. 1998) which can be used to strongly constrain spectral models. Normally, spectra in several intensity bands would be selected and then fitted simultaneously. In this case it is difficult to do this because the spectra were selected from data with 16 s binning (PCA data in Standard 2 mode) and the ingress to dipping was very rapid, on a timescale of seconds (Fig. 3, left). To avoid unnecessary mixing of data of different intensities due to this, which can make spectral fitting difficult and results erroneous, only two high quality spectra were selected: one during deep dipping, and another during persistent emission.

In fitting the dip spectrum, firstly the disc blackbody plus power law model was used without line terms. All of the emission parameters were held constant at the values determined for the non-dip spectrum, since dipping must be fitted by absorption only. In order to fit the dip spectrum, it was found necessary for the disc blackbody to have a covering fraction term implying either partial covering by a blobby absorber, or steadily increasing, progressive covering by a non-blobby absorber having angular size somewhat less than the angular size of the disc blackbody. In contrast, the power law appeared to be totally covered by a simple absorber implying smaller emission region size. This is the same model as used by Kuulkers et al. (1998) to fit the same data. However, even the best fit for the continuum-only model was poor, with a reduced \( \chi^2 \sim 2 \) and so the disc line was added to the model, for simplicity in the form of two Gaussian lines to represent

Fig. 2. Left: Unfolded spectrum of the best fit to a single spectrum, including two Gaussian lines. Right: Best-fit with a Laor-disc line + absorption line model. Two continuum components and the Laor line shown; the absorption line cannot be plotted as it has negative normalization.
the red and blue wings. The model becomes

$$\exp(-\sigma_{pe} N_{H}^{gal}) \times \{ \exp(-\sigma_{pe} N_{H}^{DBB}) \times f_{cov} + (1 - f_{cov}) \} \times (\text{DISCBB} + 2 \text{ GAUSSIAN}) + \exp(-\sigma_{pe} N_{H}^{PL}) \times \text{POWERLAW}$$

where $\sigma_{pe}$ is the photoelectric cross-section with cosmic abundances (Morrison & McCammon 1983), $N_{H}^{gal}$ is the galactic column density, $N_{H}^{DBB}$ is the disc blackbody column density, $f_{cov}$ is the covering fraction and $N_{H}^{PL}$ is the column density for the Comptonized component. The best fit model is shown in Fig. 3 (right). During dipping $N_{H}^{DBB}$ increased to $1.4 \times 10^{24}$ cm$^{-2}$, the covering fraction $f_{cov}$ reached 94% consistent with the residual intensity seen in dipping (Fig. 3), and $N_{H}^{PL}$ was much larger that $N_{H}^{DBB}$ effectively removing all the contribution of the power law component up to at least 15 keV. This implies that the size of the Comptonizing region is smaller that the X-ray emitting accretion disc. The intensity of the disc line described for simplicity by two Gaussian lines decreased during dipping and could be modelled with the same covering fraction as the disc blackbody component suggesting that the line originates in the same part of the disc as the disc blackbody. The decrease of the line is highly significant: an F-test showed a significance $>>$ 99.99%. This provides further evidence that the disc line is real.

Although X-ray dipping in GRO J1655-40 is very deep, it is not 100% deep. The depth of dipping in the energy band 2.5–25.0 keV is $\sim$91% and is independent of energy if measured in several energy bands. This rules out the possibility that the residual emission comes entirely from the dust scattered halo. The halo will contribute to the residual emission as expected for a bright source with high galactic column, but only at energies below $\sim$5 keV. The galactic column density towards GRO J1655-40 is $7.0 \pm 0.5 \times 10^{21}$ cm$^{-2}$ based on $E(B-V) = 1.3 \pm 0.1$ (van der Hooft et al. 1998) and radio measurements (Dickey and Lockman 1990). From this $N_{H}$, a dust-scattered halo contribution of only $\sim$3% to the count rate in energies 2.5–25.0 keV can be calculated. Therefore, the majority of the residual emission during deep dipping must come from uncovered disc blackbody emission. It cannot be Comptonized emission as the total contribution of the power law component is 10% only and spectral fitting shows that this is totally removed up to at least 15 keV in deep dipping. Kuulkers et al. (1998) obtain a covering fraction of 99% which appears inconsistent with the $\sim$9% of intensity remaining in deep dipping (Fig. 3). It is not surprising that this model produces a low energy excess in dipping; however, we have shown that this is due to some emission being not covered
SIZE OF THE EMISSION AND ABSORPTION REGIONS

The sizes of the emission and absorption regions can be obtained by using dip ingress and egress times, plus the duration of dipping. The technique differs according to whether the emitter or absorber has larger angular size, and in the present case that dipping is not 100% deep we cannot tell which is larger. If the absorber has larger angular size than the most extended emission, i.e. the disc blackbody, then the ingress time $\Delta t$ will be determined by the diameter of the emission region and the velocity of the absorber. The residual emission must be due to the absorber being blobby. If the absorber has smaller angular size, $\Delta t$ is determined by the absorber diameter, and the residual due to incomplete overlap of emitter and absorber. In either case, the total duration of dipping including ingress and egress is proportional to the sum of emitter and absorber diameters. Both possibilities will be discussed in the following. It is assumed that the absorber is located on the outer rim of the disc and co-rotates with the binary frame. It should also be noted that changes during dipping take place on two time-scales: firstly, there is an intensity decrease of $\sim 10$–$15\%$ from the non-dip level of $\sim 2300$ Counts s$^{-1}$ taking $\sim 45$ s which can be described as a shoulder of the dipping; this is followed by a rapid transition to deep dipping lasting 6–10 s.

Firstly, if the X-ray emitting disc is smaller than the absorber the total dip ingress time gives the disc blackbody diameter $d_{\text{DBB}}$ via the equation $2\pi r_{\text{AD}}/P = d_{\text{DBB}}/\Delta t$, where $r_{\text{AD}}$ is the accretion disc radius and $P$ the orbital period. This gives $d_{\text{DBB}} = \sim 7 \times 10^8$ cm. The total duration of dipping of $\sim 170$ s combined with this value gives an absorber diameter of $1.5 \times 10^9$ cm. A simple calculation of the surface brightness of an accretion disc with temperature of 1 keV confirms that a hot inner core would have a size of $\sim 10^8$ cm.

The linear scales of the absorber and emitter in the above cases are presented in Fig. 4. For comparison, the radius of the region emitting the iron emission line is also shown. It should be noted that the diameter of the X-ray source obtained here is substantially larger than that provided by Kuulkers et al. (1998) of $23 \, r_S$. Firstly, they assume that the angular size of absorber is much greater than that of the source which we show above may not be the case, only one possibility. Secondly, they ignored the shoulders of dipping.
lasting $\sim 45$ s. Additionally, they assumed an unrealistically short ingress/egress time of 3.5 s in comparison with the 6–10 s adopted here. Consequently, they obtained a size of the X-ray source $\sim 15$ times smaller than the value presented here. Similarly, the duration of dipping at 55 s was underestimated compared with the 170 s used here, leading to radius of $\sim 95 r_S$ compared with our 370 $r_S$.

CONCLUSIONS

In the Rossi-XTE spectra of GRO J1655-40, a highly shifted iron emission line was detected. The line originates in the inner part of the disc which rotates with relativistic velocities $\sim 0.3 c$ producing the characteristic shape of a disc line with strong Doppler broadening and boosting. The region where the line is generated is most probably highly ionized (Fe XXII) although the ionization state is not well constrained. The intensity of the emission line decreases during dipping by the same factor as the emission from the accretion disc providing further evidence that the line originates in the disc.

During deep saturated dipping, the Comptonized component is totally absorbed but 10% of the emission is still seen which must originate in the disc. It can be shown that either the outer and cooler parts of the disc are still visible during deep dipping or the absorber is blobby. In both cases, the radius of the disc core which makes the major contribution to the disc luminosity is in rough agreement with the radius of the line emitting region $\sim 30$ Schwarzschild radii. The radius of the X-ray emitting region is between 170–370 $r_S$ depending on the assumptions made about the absorber. The disc emission region is much larger than that previously reported by Kuulkers et al. (1998), who probably underestimated the dip ingress/egress times.

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