**ASCA observation of a dip of GRO J1655−40: evidence for partial covering and its implication**

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**ABSTRACT**

The X-ray spectrum of a transient dip of the black-hole binary GRO J1655−40 observed with ASCA in 1994, August, displays a deep K-absorption edge by neutral or weakly ionized iron, but the fluorescence K-line is absent. This dip of GRO J1655−40 is explained in terms of partial covering of the central X-ray emitting region, involving two layers of absorber (‘double partial covering’). The results of the spectral analysis indicate that the dip is caused by an absorber of a column density as large as one Compton depth, crossing the line of sight. The physical conditions of such absorbers imply that they are located in the outer part of the accretion disc. An interesting property of the double partial covering is that, while the intrinsic luminosity is constant, the observed flux can vary by a large factor without changing the spectral shape. This might account for some cases of variabilities of active galactic nuclei showing a similarly deep iron K-absorption.

**Key words:** X-rays: binaries – X-rays: individual: GRO J1655−40.

**1 INTRODUCTION**

GRO J1655−40 is a transient X-ray binary that underwent an outburst in 1994 July (Zhang et al. 1994). This source is known to have exhibited superluminal radio jets (Tingay et al. 1995; Hjellming & Rupen 1995). The optical observations established that GRO J1655−40 is a low-mass X-ray binary containing a black hole (Bailyn et al. 1995; Orosz & Bailyn 1997). Orosz & Bailyn (1997) obtained accurate binary system parameters from detailed optical studies, and determined the black hole mass to be 7.02 ± 0.22 M⊙.

Unlike most soft X-ray transients, GRO J1655−40 continued to show major flare-up events after the initial outburst. GRO J1655−40 was observed with ASCA several times at various flux levels between 1994 and 1997. The results of these observations, particularly the discovery of the absorption lines of highly ionized iron ions, have been reported by Ueda et al. (1998) (hereafter Paper I) and Yamaoka et al. (2001).

During the observation on 1994 August 23, a dip-like event was observed (see the light curve shown in Fig. 1). The flux decreased by a factor of about 4 and stayed low for several hours, then returned to roughly the same level as before the dip. This event was first suspected to be an eclipse of the X-ray emitting black hole by the companion star. However, this possibility was later excluded. According to the ephemeris determined by Orosz & Bailyn (1997), the star was on the far side of the black hole at that epoch. Hence, it was clearly a decrease of the X-ray flux from the source itself.

The observed energy spectra have been analysed in Paper I. Yet the nature of this dip is still left to be understood. In this paper we present the results of the detailed study of the dip, and show that it is explained satisfactorily in terms of partial covering of the X-ray source. We also discuss physical conditions of the absorber responsible for the partial covering.

**2 SPECTRAL ANALYSIS**

The light curve during the observation made on 1994 August 23, obtained with the GIS for the energy range 0.7–10 keV, and the hardness ratio between the two energy bands, 0.7–4 keV and 4–10 keV, are shown in Fig. 1. The dip lasted for about 6 h. The time-scales of the fall and rise of the dip are uncertain because of poor time coverage of the source in this observation, but appear to be no longer than half an hour. During the dip, the flux level averaged over time-scales of ~1 h was roughly constant, although significant flux variations over shorter time-scales are noticeable.

The energy spectra obtained with the gas imaging spectrometer (GIS) before the dip (‘predip’) and during the dip are shown in Fig. 2. A spectrum at a higher flux level observed on 1995 August 15 (hereafter referred to as ‘high state’) is also included for comparison. Instead of the count rate spectra, the photon spectra are presented here by correcting for only the energy dependence of the detection efficiency. They are not deconvolved with the energy resolution of the GIS, hence sharp features such as lines and edges remain as observed. The predip and dip spectra look similar in shape up to about 7 keV, whereas the depth of the iron K-absorption edge at 7.1 keV

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is distinctly deeper during the dip. The GIS spectra are investigated in detail here. Although the solid-state imaging spectrometer (SIS) is superior to the GIS in energy resolution, it suffers severe photon pile-up for such a bright source that affects the shape of the observed continuum.

It was shown in Paper I that partial covering of a cut-off power-law model of the form $E^{-\gamma}e^{-E/E_c}$ approximately reproduces the observed predip and dip spectra. The following analysis is also carried out based on the concept of partial covering. Instead of the cut-off power law employed in Paper I, we utilize here the multicolour blackbody disc (MCD) model (Mitsuda et al. 1984) that describes the emission spectrum from an optically thick accretion disc. The soft thermal component of the black hole binaries in the high-luminosity/soft state is believed to come from such a disc, and the MCD model is known to explain the soft component satisfactorily (see e.g. Tanaka & Shibazaki 1996). This model contains two parameters; the innermost disc temperature $kT_{in}$ and a normalization factor. In fact, the high-state spectrum of GRO J1655–40 is well fitted by the MCD model below 6 keV, above which a hard tail begins to show up. The best-fitting MCD model parameters are listed in Table 1. Note that the cut-off power-law model can produce practically the same shape as the MCD model in the ASCA energy band, and used in Paper I only for the purpose of fitting the continuum.

Similar to the result in Paper I, the predip and dip spectra can be fitted with a partial covering model for the MCD spectrum as well, consisting of a non-absorbed (except for interstellar absorption) and a heavily absorbed component. However, the derived values of the foreground hydrogen column for the non-absorbed component, $<10^{21}$ cm$^{-2}$ (see also table 2 of Paper I), are found too small to be compatible with the optical reddening of the source. The observed colour excess $E(B-V)=1.3 \pm 0.1$ (Horne, Harlaftis & Baptista 1996) suggests an interstellar hydrogen column $N_H^*$ of $\sim$ several $\times 10^{21}$ cm$^{-2}$ (see Predelh & Schmitt 1995). The small value of $N_H^*$ is considered to be due to the presence of a softer component, probably a delayed dust-scattered component originating in the preceding period when the flux level was presumably higher. Assuming that it is the case and that the scattered component was constant before and during the dip, one can determine the true $N_H^*$ value and the contribution of the scattered component.

The scattered component is cancelled out by taking the difference between the predip and dip spectra. Fitting the difference spectrum with a MCD model, we obtain $N_H^*=(4.5 \pm 1.5) \times 10^{21}$ cm$^{-2}$ for $kT_{in}=1.25 \pm 0.11$ keV. This $N_H^*$ value is consistent with the observed colour excess. Therefore, $N_H^*$ is fixed at $4.5 \times 10^{21}$ cm$^{-2}$ in the following analysis. Then, the scattered component common to the predip and dip spectra is determined, assuming a form $\propto F_{MCD}(E) \cdot E^{-\gamma}$, where $kT_{in}$ obtained for the high-state spectrum is used (see Table 1).

Both the predip and dip spectra are fitted with the partial covering model expressed by the formula

$$e^{-\alpha N_H^*} \left[ \left\{ f e^{-\alpha N_H^*} + (1-f) \right\} F_{MCD}(E) + S(E) \right],$$

where $f$ denotes the covering fraction of a line-of-sight absorber of a column density $N_H^*$, and $S(E)$ is the above-determined scattered component. The solar abundances are assumed for the absorbing material. For the predip spectrum, the absorption lines and edges from highly ionized iron ions reported in Paper I are also included. No such features are evident in the dip spectrum. The results of the fit are shown in Figs 3(a) and (b), and the best-fitting parameters are given in Table 1. Hard tails are insignificant in these spectra.

As regards the dip spectrum, although the overall fit is acceptable, systematic deviations of the data points around 7 keV are noticed. More importantly, the obtained parameter values contain physical inconsistencies, which are discussed in the next section. The fit improves substantially when a second partial covering is introduced, i.e.

$$\left\{ f e^{-\alpha N_{H_1}} + (1-f) \right\} \left\{ f_2 e^{-\alpha N_{H_2}} + (1-f_2) \right\} F_{MCD}(E),$$

which involves three absorbed components with different column densities, $N_{H_1}, N_{H_2}$, and $N_{H_1} + N_{H_2}$, respectively. The fit result of this ‘double partial covering’ is shown in Fig. 4, and the best-fitting parameters are given in the last column of Table 1.

As noticed in Table 1, the main differences between the single and double partial covering models are found in the values of the intrinsic luminosity $L_0=(4\pi d^2) L_\odot$ for the distance $d$ and $N_{H_1}$. The former model gives a decrease of $L_0$ by a factor of $\sim 3$ and a large increase of $N_{H_1}$ after the transition, whereas the latter gives essentially the same values before and during the dip within statistical uncertainties. These and other differences are discussed in the next section.

Table 1. Results of the spectral fit with the partial covering model.

<table>
<thead>
<tr>
<th></th>
<th>1995 August high state</th>
<th>1994 August predip</th>
<th>1994 August dip</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{\text{obs}}$ (erg cm$^{-2}$ s$^{-1}$)</td>
<td>$3.7 \times 10^{-8}$</td>
<td>$6.8 \times 10^{-9}$</td>
<td>$1.7 \times 10^{-9}$</td>
</tr>
<tr>
<td>$N_{\text{H}}$ (10$^{22}$ cm$^{-2}$)</td>
<td>0.63 (fixed)</td>
<td>0.45 (fixed)</td>
<td>0.45 (fixed)</td>
</tr>
<tr>
<td>$kT_{\text{in}}$ (keV)</td>
<td>1.37</td>
<td>$1.28 \pm 0.02$</td>
<td>$1.34 \pm 0.02$</td>
</tr>
<tr>
<td>Norm.</td>
<td>870</td>
<td>520 $\pm$ 50</td>
<td>140 $\pm$ 20</td>
</tr>
<tr>
<td>$I_0$ (erg cm$^{-2}$ s$^{-1}$)</td>
<td>$3.7 \times 10^{-8}$</td>
<td>$1.7 \times 10^{-8}$</td>
<td>$0.6 \times 10^{-8}$</td>
</tr>
<tr>
<td>$f$</td>
<td>0</td>
<td>$0.65 \pm 0.02$</td>
<td>$0.77 \pm 0.02$</td>
</tr>
<tr>
<td>$N_{\text{H}}$ (10$^{22}$ cm$^{-2}$)</td>
<td>$46 \pm 3$</td>
<td>$75 \pm 4$</td>
<td>$43 \pm 11$</td>
</tr>
<tr>
<td>$f_2$</td>
<td>0</td>
<td>0</td>
<td>$0.80 \pm 0.08$</td>
</tr>
<tr>
<td>$N_{\text{H,2}}$ (10$^{22}$ cm$^{-2}$)</td>
<td>0</td>
<td>0</td>
<td>150 $^{+70}_{-40}$</td>
</tr>
<tr>
<td>$\chi^2/\nu$</td>
<td>92/78</td>
<td>105/82</td>
<td>86/80</td>
</tr>
</tbody>
</table>

Notes. *A weak hard tail is present above 6 keV. $I_{\text{obs}}$ and $I_0$ are the observed and intrinsic source flux ($I_0 = L_0/4\pi d^2$) in 2–10 keV, respectively. $f_2$ and $N_{\text{H,2}}$ are the covering fraction and the column density of a second absorber.

3 DISCUSSION

3.1 Origin of the dip

The results of the spectral analysis of the black-hole binary GRO J1655−40 before and during the dip observed on 1994 August 23 are presented in the previous section. GRO J1655−40 was most likely in a soft state in this period because of the observed soft thermal spectrum that is well expressed by the MCD model representing the emission from an optically thick disc.

The observed dip is characterized by a flux decrease by a factor of ~4 and a distinct deepening of the iron K-absorption edge. The
mixing of higher-energy edges of iron ions as well as the Compton ionized disc (which is favourable), the edge is also broadened due to Compton blurring smears out the increases with the degree of photoionization of the disc. While the central X-ray source is compact, the following two cases of partial covering are conceivable: (i) the X-ray emitting region appears extended as a result of Thomson scattering in a tenuous plasma above the inner disc (disc corona), and a part of the scattered X-rays clear the absorber that obscures the central source; and/or (ii) the absorber is patchy so that a fraction of the direct beam can leak through (sometimes called ‘leaky absorber’ model). The absence of the fluorescence line requires that the absorber does not subtend a large solid angle ($<2\pi$) viewed from the central X-ray source but is more or less localized crossing the line of sight. The observed dip was most probably caused by a cloud that crossed the line of sight during its orbital motion. The result of the analysis summarized in Table 1 indicates that such a cloud has a column density of the order of one Compton depth.

The dip spectrum was analysed in two ways; a single partial covering and a double partial covering. The single partial covering model gives a poor fit around 7 keV. Besides, a single partial covering interpretation involves the following fundamental problems. The present result shows that the source was already in a partial covering situation during the predip period. Compared with the predip, the result for the dip indicates not only a large increase of the column density of the absorber $N_H$ but also a simultaneous decrease of the intrinsic luminosity $L_0$ by a factor of $\sim 3$. However, because the absorber is likely to be located far away from the centre (as far as $10^{12}$ cm, see later discussion), such correlated changes are implausible. In addition, a significant increase of $kT_{in}$ against a decrease of the intrinsic luminosity is opposite to the general trend for black hole binaries in the soft state, i.e. usually $kT_{in}$ decreases when $L_0$ decreases (see e.g. Tanaka & Lewin 1995; Tanaka 1997).

On the other hand, the double partial covering model not only gives an excellent fit, but also reveals several interesting features. From Table 1, the most important result is that $L_0$ and $kT_{in}$ remain the same before and after the transition into the dip, i.e. no change occurred in the central source. Also, the covering fraction $f$ and the column $N_H$ of the pre-existing absorber are essentially unchanged throughout the predip and dip. Thus, according to the double partial covering scenario, the dip is caused solely by another absorber crossing the line of sight. This interpretation of the dip seems to be phenomenologically self-consistent. It is to be noted that double partial covering is a simplified model for possibly more complex covering with multiple absorption layers.

In what follows, we investigate the physical conditions of the partial covering absorbers in order to examine the overall consistency of the model.

### 3.2 Physical conditions of the absorber

Suppose the absorber is the material extending above the disc plane at a distance $r$ from the centre. If it is in hydrostatic equilibrium, the temperature is approximately given by

$$kT \sim (GMm_p/(r))(h/r)^2,$$

where $h$ is the scaleheight. We assume here that the height of the absorber from the plane is comparable to $h$. Then, $h/r = \cot i,$
where \( i \) is the inclination and \( \sim 70^\circ \) for GRO J1655–40 (Orosz & Bailyn 1997).

The observed energy and the sharpness of the iron K-edge imply that iron in the absorber is mostly in the states Fe I–Fe III. This requires \( kT \lesssim 0.1 \text{ keV} \) (e.g. Arnaud & Raymond 1992). Therefore, \( r \gtrsim 10^4 r_g \) from the above equation, where \( r_g \) is the gravitational radius. This corresponds to \( r \gtrsim 10^{12} \text{ cm} \) for GRO J1655–40, of which \( r_g \sim 10^6 \text{ cm} \). This is comparable to the binary system size of GRO J1655–40, and hence implies that the absorber is located in the outermost part of the disc. Another possibility is that the absorber is clumpy. In this case, the above hydrostatic equilibrium does not necessarily hold, and the absorber may be located at a smaller distance than \( 10^{12} \text{ cm} \).

As the source is very luminous, the effect of photoionization should be examined. We estimate it with the photoionization parameter \( \xi = L_0/nr^2 \text{ erg cm}^{-1} \text{ s}^{-1} \), where \( n \) is the atomic density. Near neutrality of iron requires \( \xi \lesssim 1 \) (Kallman & McCray 1982). For the values of \( L_0 \) in Table 1, \( L_0 \gtrsim 2 \times 10^{37} \text{ erg s}^{-1} \) (for \( d = 3.2 \text{ kpc} \), see Hjellming & Rupen 1995), and we obtain a condition that \( n \gtrsim 10^{10} (r/10^{12} \text{ cm})^{-2} \text{ cm}^{-3} \). For comparison, the gas density of the disc is estimated from the Shakura & Sunyaev disc theory (1973), which gives \( \sim 10^{12} \text{ cm}^{-2} \) at \( r \sim 10^{12} \text{ cm} \) for a viscosity parameter \( \alpha = 0.1 \). This is consistent with the above condition. The column density of the absorber \( N_{\text{HI}} = n_0 \Delta r \sim 10^{24} \text{ cm}^{-2} \) (see Table 1), where \( n_0 \) is the average density over the radial thickness of the absorbing layer \( \Delta r \). In case that the absorbing matter is homogenous, the condition \( \xi \lesssim 1 \) is satisfied if \( \Delta r \lesssim 10^{11} \text{ cm} \) for a distance \( r \sim 10^{12} \text{ cm} \). The observed dip lasted for about 6 h. Assuming the Keplerian motion, the absorber responsible for the dip has a longitudinal extent of \( \sim 5 \times 10^{11} \text{ cm} \) for \( r \sim 10^{12} \text{ cm} \), which fills about one tenth of the Keplerian orbit, and is stretched along the orbit.

The present result indicates that the source was already in a partial covering situation in the predip period. This part of absorption is found to be rather stationary, continuing through the dip. The geometric relation between the first and the second covering zones is unknown. However, it is likely that the stationary one is more inside, since matter in the inner zones will be more uniformly distributed along the orbit by differential rotation.

### 3.3 Properties of double partial covering

As an interesting consequence of the present results, it can be shown in case of double partial covering that, for a fixed intrinsic luminosity, the observed flux may change by a large factor without significant changes in the spectral shape, if \( f_2 \) and \( N_{\text{HI},2} \) are positively correlated. In Fig. 5 are shown a group of spectra produced with the double partial covering model, based on the results given in Table 1. The intrinsic spectrum (marked ‘a’) is the one derived for the predip spectrum in Section 2, which is essentially the same as that for the dip spectrum in the double partial covering case. The curve (‘b’) corresponds to the predip spectrum for single covering with the parameter values in Table 1. The curves ‘c’–‘f’ are those computed for various sets of \( (f_2, N_{\text{HI},2}) \), while the parameter set of the first covering \( (f, N_{\text{HI}}) \) is fixed at \( (0.65, 4.6 \times 10^{23} \text{ cm}^{-2}) \) as given in Table 1. The parameter sets \( (f_2, N_{\text{HI},2}) \) for c–f are \((0.53, 2 \times 10^{24} \text{ cm}^{-2}), (0.80, 1.5 \times 10^{24} \text{ cm}^{-2}), (0.91, 2.2 \times 10^{24} \text{ cm}^{-2}), (0.95, 2.7 \times 10^{24} \text{ cm}^{-2})\), respectively. The curve ‘d’ corresponds to the dip spectrum. The \( f_2 \)-value is chosen arbitrarily except for ‘d’ in order to change the ‘observed’ flux, whereas \( N_{\text{HI}} \) is determined for each case so as to reproduce the closest spectral shape to the dip spectrum. As seen in Fig. 5, little change in the spectral shape is noticed from ‘c’ through to ‘f’ against the flux change by more than an order of magnitude.

Positive correlation between \( f_2 \) and \( N_{\text{HI},2} \) is plausible. In the case of an absorber in hydrostatic configuration, the increase of gas density and/or of the scaleheight will increase both \( L_{\text{HI}} \) and \( \Delta \), although modelling the covering with these two parameters is a simplified approximation and it is difficult to show the correlation quantitatively. Positive correlation between \( f_2 \) and \( N_{\text{HI},2} \) is also expected when the absorber is clumpy, consisting of individual clouds. The larger the covering fraction, the more is the number of clouds crossing a line of sight. In this case, one can estimate the relation between \( f_2 \) and \( N_{\text{HI},2} \) as follows: suppose the number of clouds on a line of sight \( n \) follows the Poisson distribution, \((1 - f_2) \) is given by \( e^{-\bar{v}} \), where \( \bar{v} = \text{average of } n \). The above \( f_2 \) values (0.53, 0.80, 0.91, and 0.95) correspond to \( \bar{v} \approx 0.8, 1.6, 2.4, 3.0 \), respectively. Therefore, for an average column density of a single cloud of \( \sim 10^{24} \text{ cm}^{-2} \), the expected column densities of the covering clouds are roughly equal to the \( N_{\text{HI},2} \)-values obtained above.

Furthermore, rapid flux variations may occur when the distribution of matter along the Keplerian orbit is not uniform. If \( N_{\text{HI}} \) changes in a longitudinal length-scale of \( \Delta l \), the time-scale of flux variation is given by \( \Delta t = (\Delta l/c) \cdot (r/r_g)^{1/2} \), independent of the mass of the central object. For example, the observed time-scale of transition into and out of the dip \( \Delta t \sim 10^3 \text{ s} \) is explained by the change in \( N_{\text{HI}} \) within a zone of \( \Delta l \sim 1 \text{ light-second} \) around the edge of the cloud at a distance \( r \sim 10^9 r_g \).

These properties of double partial covering might have relevance to some cases of active galactic nuclei (AGN). For instance, NLSy1 1H0707–495 shows a strong non-absorbed component and a very deep K-absorption edge of essentially neutral iron without significant fluorescence line, which is qualitatively similar to the case of GRO J1655–40 during the dip. In fact, Boller et al. (2002) found that two absorbed components are necessary in order to reproduce the observed spectrum of 1H0707–495 with partial covering model. Also, 1H0707–495 displays some of the most rapid variability among AGN, on time-scales \( \lesssim 10^3 \text{ s} \). Remarkably, it showed little change in the spectral shape against large flux variation (Boller et al. 2002).
As shown above, changes in partial covering at large distances from the centre can cause such variabilities. This result suggests that, for AGN that exhibit partial covering signature such as 1H0707–495, some of the variabilities, if not all, might possibly be caused in the similar way, rather than the changes of the central source on such short time-scales that require some extreme physical conditions. Brandt & Gallagher (2000) suggested similar possibility for the extreme X-ray variability of some NLSy1, which is difficult to explain as true luminosity changes. Application of the double partial covering model to 1H0707–495 is presented in a separate paper (in preparation).

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