BROADBAND X-RAY SPECTRA OF THE BLACK HOLE CANDIDATE GRO J1655—40

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ABSTRACT

We present broadband (2 keV–2 MeV) X-ray spectra of GRO J1655—40, a luminous X-ray transient and occasional source of relativistic radio jets, obtained with the Rossi X-Ray Timing Explorer (RXTE) and the Oriented Scintillation Spectrometer Experiment. In one observation, the luminosity is found to be 18% of the Eddington limit, which is one of the highest luminosities ever observed from GRO J1655—40. For this observation, we find that an adequate fit is obtained when a broad iron line and a reflection component are added to a model consisting of a power law plus a soft excess component. The 95% confidence lower limit on the redshift width of the iron line is 0.86 keV. The power-law component has a photon index of 2.72 ± 0.08 and extends to at least 800 keV without a cutoff. After this observation, a significant drop in the (5–12 keV)/(1.5–5 keV) hardness ratio occurred on a timescale less than 2 hr. From an RXTE observation of GRO J1655—40 made after the hardness transition, we find that the power-law index is harder (α = 2.415 ± 0.011), the flux of the power-law component is lower, and the total luminosity is 10% of the Eddington limit. The change in the power-law component is consistent with the correlation between the spectral index and power-law flux previously reported for GRO J1655—40.

Subject headings: accretion, accretion disks — black hole physics — radiation mechanisms: nonthermal — stars: individual (GRO J1655—40) — X-rays: stars

1. INTRODUCTION

The X-ray transient GRO J1655—40 was discovered with the Burst and Transient Source Experiment (BATSE) on the Compton Gamma-Ray Observatory (CGRO) on 1994 July 27 (Zhang et al. 1994). GRO J1655—40 is often called a microquasar because radio jets moving at 92% of the speed of light relative to the X-ray source have been observed (Tingay et al. 1995; Hjellming & Rupen 1995). From optical observations of GRO J1655—40 an excellent laboratory for learning about accreting black holes.

Since the discovery of GRO J1655—40, its 20–200 keV X-ray flux has been monitored by BATSE (Tavani et al. 1996). In the BATSE bandpass, a power-law spectrum is observed with a photon index varying between 1.8 and 3.1. The BATSE data suggest that the photon index softens as the source intensity increases (Wilson et al. 1995; Zhang et al. 1995). This trend has also been reported from observations of GRO J1655—40 by the Oriented Scintillation Spectrometer Experiment (OSSE) on CGRO (Grove et al. 1998). OSSE measurements of GRO J1655—40 have been made between 1994 August and 1996 September. During observations where the source was detected, the spectrum in the OSSE bandpass is consistent with a power law (Kroeger et al. 1996; Grove et al. 1998). In this paper we report on simultaneous Rossi X-Ray Timing Explorer (RXTE) and OSSE observations of GRO J1655—40 made in 1996. Soft X-ray measurements of the source made with the Advanced Satellite for Cosmology and Astrophysics (ASCA) indicate the presence of an ultrasoft component (Zhang et al. 1997a), which probably comes from an accretion disk around the compact object.

Previous spectral and timing measurements of GRO J1655—40 have been interpreted as evidence that the compact object in this system is a rapidly rotating black hole (Zhang, Cui, & Chen 1997b; Cui, Zhang, & Chen 1998a). Similar results have been obtained for another microquasar, GRS 1915+105, suggesting that the relativistic, highly collimated radio jets in the microquasars are related to the presence of a rapidly rotating black hole (Zhang et al. 1997b). Black hole rotation rate has long been considered as a way to explain the radio-loud/radio-quiet dichotomy in active galactic nuclei (AGNs; Wilson & Colbert 1995).

In this paper, we report on simultaneous observations of GRO J1655—40 made by RXTE and OSSE. After describing the observations and our analysis techniques, we present the results of the spectral fits. We then discuss the results and end with our conclusions.

2. OBSERVATIONS

Figure 1 shows the GRO J1655—40 RXTE All-Sky Monitor (ASM) light curve and (5–12 keV)/(1.5–5 keV) hardness ratio from late August to early September of 1996 when GRO J1655—40 was observed simultaneously with RXTE and OSSE. OSSE observations were made following observations by BATSE, indicating that GRO J1655—40 had undergone several strong outbursts since mid-July of 1996. The decision to observe GRO J1655—40 came during the fifth outburst of this series above 1 crab in the 20–100 keV energy band. These RXTE and OSSE observations occur during one of the highest luminosity and hardest states of GRO J1655—40 (Remillard et al. 1998). A
sharp change in the ASM hardness is seen at MJD 50,328.5, which is marked with a vertical dotted line in Figure 1. For the 6 days before the transition, the ASM count rate is constant (in 1 day averages) to ±6%, with a mean value of 220 ± 2 s⁻¹, corresponding to about 2.9 crab. Over the same time period, the mean hardness ratio is 0.449 ± 0.003.

At the transition, the hardness changes on a timescale less than 2 hr, while the 1.5–12 keV flux dips sharply, recovers, and then decays to a constant level in about 1.5 days. During the time from MJD 50,330 to 50,335, the mean ASM count rate is 170 ± 1 s⁻¹, and the 1 day averages vary by ±4%. The OSSE observation was made from MJD 50,328.5 to 50,328.4 and lies completely in the time interval of high X-ray hardness. Pointed RXTE observations, marked with arrows in Figure 1b, were made on MJD 50,324.4 and 50,330.3. One RXTE observation is during the OSSE observation, and the other is after the hardness transition. The first RXTE observation contains 4334 s of Proportional Counter Array (PCA) live time and 2929 s of High-Energy X-Ray Timing Experiment (HETIME) live time (on-source). The second RXTE observation contains 5618 s of PCA live time and 3715 s of HEXTE live time.

GRO J1655–40 radio observations were made with the Very Large Array (VLA) and the Molonglo Observatory Synthesis Telescope (MOST) close to the time of the RXTE and OSSE observations (R. M. Hjellming & R. Hunstead 1997, private communication). GRO J1655–40 was not detected for any of the radio observations. Observations were made by the VLA on MJD 50,323, 50,326, 50,330, and 50,337 resulting in upper limits of 0.4 mJy, and observations were made by MOST on MJD 50,306, 50,313, 50,326, and 50,340 resulting in an upper limit of 4 mJy.

3. ANALYSIS

PCA energy spectra have been produced using Standard 2 PCA data and the Version 2.2.1 (1998 January 20) response matrix. During the pre-transition observation, Proportional Counter Unit (PCU) 3 was off. To test the PCA response matrix for the remaining PCUs (0, 1, 2, and 4), we fitted the Crab spectrum with a power law. Crab spectra have been extracted from an 11.6 ks observation made between MJD 50,529.9 and 50,530.2. We produced spectra containing data from all three xenon layers and also from only the top xenon layer. In both cases, power-law fits to the Crab are significantly better for PCUs 0, 1, and 4 than for PCU 2. Also, the top-layer spectra give column densities and photon indices that are closer to the conventional values for the Crab (Toor & Seward 1974; Koyama et al. 1984; Schattenburg & Canizares 1986; Turner et al. 1989) than the spectra for all three layers combined. Thus the GRO J1655–40 spectral analysis has been performed using events from the top layers of PCUs 0, 1, and 4. Although PCU 3 was on during the post-transition observation, it has not been used in order to avoid instrumental differences between the pre-transition and post-transition spectra. A systematic error of 1% is assumed to account for uncertainties in the response matrix, and the normalizations have been left free between PCUs. Spectral bins from 2.5–20.0 keV have been used for the spectral analysis. Background subtraction has been performed including estimates for the particle, X-ray, and activation background spectra; however, for both spectra, activation does not contribute to the background. The spectra have been corrected for dead time.

We find that pile-up has a significant impact on the GRO J1655–40 PCA spectrum. The ratio of the pile-up spectrum to the measured spectrum reaches a maximum of 5% near 18 keV for the pre-transition spectrum, while the ratio reaches a maximum of 5% near 13 keV for the post-transition spectrum. Thus a correction for pile-up has been applied as described by J. A. Tomsick and P. Kaaret.

HETIME energy spectra have been produced using Standard mode data, which consist of 64 bin spectra with 16 s time resolution. The 1997 March 20 HETIME response matrices have been used. For HETIME, it is essential to correct for dead time (Rothschild et al. 1998), and this correction has been made. For the spectral fits, the normalizations have been left free between cluster A and cluster B.

OSSE made its standard observation over a period of 6 days by pointing its collimator at GRO J1655–40 and comparing this with count rates in background fields 4:5 on either side of the source. Because of the large field of view of OSSE, ~3°8 by 11°4 FWHM response, the observations have potential problems with source confusion. Nearby sources 4U 1700–37 and OAO 1657–415 are not significant sources above 100 keV in comparison to GRO J1655–40 and can be ignored. To make sure that the OSSE data is not contaminated because of source confusion, we compared the OSSE spectrum to the HETIME spectrum in the energy band where the two instruments overlap. We find that the OSSE and HETIME spectra are consistent, up to a constant normalization factor, in this energy band. Narrow-line

5 From K. Jahoda 1997, XTE-PCA: http://lheawww.gsfc.nasa.gov/docs/xray/xte/pcan.
6 From M. Stark 1997, PCABACKEST (for URL, see footnote 5).
7 PILE-UP (for URL, see footnote 5).
We find that PCUs 0, 1, and 4 measure 2.5 - 1984; Schattenburg & Canizares 1986; Turner et al. 1989). Other instruments (Toor & Seward 1974; Koyama et al. the PCA to previous measurements of the Crab flux by fluxes measured by HEXTE and OSSE spectra without the data from the PCA. Since a power law does not provide an acceptable fit ($\chi^2/\nu = 197/140$), more complicated models were used to improve the fit. The fit results are shown in Table 1. A model consisting of a power law with an exponential break (cutoff power law) gives $\chi^2/\nu = 149/139$, which is a significant improvement over a power law. The photon index and folding energy are found to be $2.703 \pm 0.010$ and $1086^{+195}_{-145}$ keV, respectively. The error estimates given here and throughout the text are 68% confidence for one interesting parameter ($\Delta \chi^2 = 1.0$). A similar improvement is observed using a model consisting of a power law with a reflection component (Magdziarz & Zdziarski 1995). For this fit, we fixed the inclination angle to $69.5^\circ$, which is the binary inclination angle measured by Orosz & Bailyn (1997), and assumed that the reflecting material has cosmic abundances. We find that the photon index and covering fraction ($\Omega/2\pi$) are $2.739 \pm 0.006$ and $0.396 \pm 0.065$, respectively, and that the spectral shape is consistent with the reflecting material being unionized. A broken power law with a break at $63_{-14}^{+9}$ keV also provides a good fit to the data. The photon indices for this fit are shown in Table 1.

When the PCA data is added to the pre-transition spectrum, a soft excess is observed, which is probably due to emission from an accretion disk. We first use a disk-blackbody component (Makishima et al. 1986) to model the soft excess. The disk-blackbody model we use is not standard in XSPEC version 10. The difference between our

annihilation radiation from the Galactic plane could potentially be a source of contamination; however, for this observation, the orientation of the spacecraft was chosen to minimize this contamination. No evidence for 511 keV line emission from GRO J1655 − 40 was detected in these observations.

The normalizations between the PCA, HEXTE, and OSSE have been left free. To estimate the GRO J1655 − 40 flux, we have compared the Crab nebula flux measured by the PCA to previous measurements of the Crab flux by other instruments (Toor & Seward 1974; Koyama et al. 1984; Schattenburg & Canizares 1986; Turner et al. 1989). We find that PCUs 0, 1, and 4 measure 2.5−25 keV Crab fluxes of 3.43, 3.38, and 3.29 (±0.05) photons cm$^{-2}$ s$^{-1}$, respectively, while previous measurements give 2.91 ± 0.03 photons cm$^{-2}$ s$^{-1}$ in the same energy band. When fluxes or spectral component normalizations are given in this paper, they have been reduced by a factor of 1.18 so that the PCA flux scale is in agreement with previous instruments. Spectral fits have been calculated using the version 10 XSPEC software (Shafer et al. 1991).

4. SPECTRAL RESULTS

We first fitted the pre-transition GRO J1655 − 40 HEXTE and OSSE spectra without the data from the PCA. We then added the PCA data to the pre-transition spectrum. When the PCA data is added to the pre-transition spectrum, a soft excess is observed, which is probably due to emission from an accretion disk. We first use a disk-blackbody component (Makishima et al. 1986) to model the soft excess. The disk-blackbody model we use is not standard in XSPEC version 10. The difference between our

### Table 1

| Parameter | Value |
|-----------|-------|
| $\alpha$ | 2.758 ± 0.005 |
| $\chi^2/\nu$ | 197/140 |

### Table 2

| Model | $\chi^2/\nu$ Pre-transition | $\chi^2/\nu$ Post-transition |
|-------|-----------------------------|-----------------------------|
| DBB + power-law | 391/274 | 187/221 |
| DBB + power-law + reflection | 244/273 | 187/220 |
| DBB + Gaussian + power-law | 220/271 | 175/218 |
| DBB + Gaussian + power-law + reflection | 191/270 | 175/217 |

### Table 3

| Model | $\chi^2/\nu$ Pre-transition | $\chi^2/\nu$ Post-transition |
|-------|-----------------------------|-----------------------------|
| COMP + power-law | 291/273 | 188/220 |
| COMP + power-law + reflection | 229/272 | 188/219 |
| COMP + Gaussian + power-law | 218/270 | 155/217 |
| COMP + Gaussian + power-law + reflection | 171/269 | 155/216 |
model and the standard XSPEC disk-blackbody model (diskbb) is that we use the relation between temperature and radius given in equation (3.23) of Pringle (1981). For our model, which is described in more detail in Tomsick, Lapshov, & Kaaret (1998), the spectrum is determined by the normalization, \( N_{\text{DBB}} \), and the maximum disk color temperature, \( T_{\text{max}} \). The normalization is given by

\[
N_{\text{DBB}} = \frac{\cos i}{f^2} \left( \frac{R_{\text{in}}/1 \text{ km}}{d/10 \text{ kpc}} \right)^2,
\]

where \( i \) is the disk inclination, \( f \) is the color correction factor, \( R_{\text{in}} \) is the inner radius of the disk, and \( d \) is the distance to the source. In the following, we assume that \( f = 1.7 \pm 0.2 \) (Shimura & Takahara 1995; Zhang et al. 1997b) and that \( d = 3.2 \pm 0.2 \) (Hjellming & Rupen 1995). We also model the soft excess using a Comptonization component (Sunyaev & Titarchuk 1980) rather than the disk-blackbody. The Comptonization model approximates the situation where soft X-rays from the accretion disk are upscattered in a plasma above the accretion disk. It is important to note that the Comptonization model we use only applies if the plasma is relatively optically thin (\( \tau > 3 \)) and the electrons in the plasma are nonrelativistic (i.e., \( kT_e \lesssim m_e c^2 \)). After the spectra are fitted using this Comptonization model, it will be necessary to check that the fit parameters satisfy these conditions. A disk-blackbody plus power-law model does not provide a formally acceptable fit to the pre-transition spectrum (\( \chi^2/\nu = 391/274 \)). A Comptonization plus power-law model provides a significantly better fit; however, it is still not formally acceptable (\( \chi^2/\nu = 291/273 \)). As shown in Figures 2a and 2b, significant systematic features are seen in the residuals for both models.

To see if the systematic features in the GRO J1655—40 residuals are due to problems with understanding the instrument responses, we produced PCA and HEXTE Crab spectra. To make the spectra, we used data from the 11.6 ks Crab observation mentioned previously. The Crab spectra were created using the same procedures as for the GRO J1655—40 data. We note that only top layer PCA data are used. The Crab spectra and the residuals for a broken power-law fit are shown in Figure 3. The data is well fitted with a broken power law (\( \chi^2/\nu = 146/221 \)). The systematic features that are observed in the GRO J1655—40 residuals are not seen in the Crab residuals; thus we assume that the features in the GRO J1655—40 residuals are not due to problems in understanding the instrument responses.

The positive residuals in the pre-transition spectrum between 6 and 8 keV suggest the presence of an iron line. Since an iron line is expected if reflection is being observed, we choose to model the high-energy portion of the spectrum using a power law with a reflection component. Thus, in the following, we use a model consisting of a soft component (disk-blackbody or Comptonization), a Gaussian emission line, and a power law with a reflection component to fit the GRO J1655—40 spectra. As shown in Tables 2 and 3, similar results are obtained using the disk-blackbody model and the Comptonization model. Specifically, we find that both reflection and the Gaussian emission line are necessary at more than 99% significance. Henceforth, model 1 will refer to a model consisting of a disk-blackbody, a Gaussian emission line, a power law, and reflection; model 2 will refer to a model consisting of a Comptonization component, a Gaussian emission line, a power law, and reflection.

The fit parameters for the model 1 and 2 fits to the pre-transition spectrum are shown in Tables 4 and 5, respectively. For the reflection component, we measure a covering fraction of 0.259 \( \pm \) 0.053 using model 1 and 0.85 \( \pm \) 0.25 using model 2. Using model 1, we find that the iron line centroid (\( E_{\text{line}} \)) is 6.81 \( \pm \) 0.54 keV and that the equivalent width is 113 eV. For model 2, \( E_{\text{line}} = 6.21 \pm 0.33 \) keV, and the equivalent width is 319 eV. In both cases, the line is very broad. The 95% confidence lower limit (\( \Delta \chi^2 = 4.0 \)) on the width of the line (\( \sigma_{\text{line}} \)) is 0.86 and 1.42 keV for models 1 and 2, respectively. The residuals for models 1 and 2 fits to the pretransition spectrum are shown in Figures 2c and 2d, respectively, and the pre-transition spectrum, fitted using model 1, is shown in Figure 4a. For both models, the iron line centroid does not constrain the ionization state of the reflecting material. Thus, to constrain the ionization state of the material, we freed the ionization parameter (\( \xi \)) in the reflection model, and, assuming a disk temperature of 10^5 K (Cui et al. 1998b), we refitted the spectra. For models 1 and 2, we find that the best value for \( \xi \) is 0.0, and, for this parameter, we derive 95% confidence upper limits on \( \xi \) of 1380 ergs cm \(^{-1}\) and 48 ergs cm \(^{-1}\) for models 1 and 2, respectively. Although the spectrum is consistent with the reflecting material being unionized, \( \xi \) is not very well constrained. The fact that \( \xi \) is not well constrained is not surprising because of the presence of the broad iron line. For model 2, we find that the conditions for the validity of the Comptonization model are met. Specifically, we find that \( \tau = 7.64 \pm 0.75 \) and that the Comptonization component is responsible for less than 1% of the flux for all energies greater than 28 keV, indicating that relativistic corrections to this model are not significant in this case.

### Table 4

| Parameter | Pre-transition | Post-transition |
|-----------|----------------|-----------------|
| Disk-Blackbody | | |
| \( kT_{\text{in}} \) (keV) | 1.489 \( \pm \) 0.023 | 1.227 \( \pm \) 0.004 |
| \( N_{\text{DBB}} \) | 49.0 \( \pm \) 2.7 | 245.8 \( \pm \) 4.2 |
| Flux (photons cm \(^{-2}\) s \(^{-1}\)) | 2.39 | 5.00 |
| Power Law | | |
| \( \pi \) | 2.747 \( \pm \) 0.006 | 2.416 \( \pm \) 0.009 |
| Flux (photons cm \(^{-2}\) s \(^{-1}\)) | 7.98 \( \pm \) 0.23 | 1.742 \( \pm \) 0.049 |
| Gaussian | | |
| \( E_{\text{line}} \) (keV) | 6.81 \( \pm \) 0.24 | 6.81* |
| \( \sigma_{\text{line}} \) (keV) | 1.21 \( \pm \) 0.20 | 1.21* |
| \( N_{\text{line}} \) (photons cm \(^{-2}\) s \(^{-1}\)) | 0.057 \( \pm \) 0.022 | 0.0107 \( \pm \) 0.0036 |
| EW (eV) | 113 | 38 |
| Reflection | | |
| \( \Omega/2\pi \) | 0.259 \( \pm \) 0.053 | 0.0* |
| \( \theta \) | 69.5 | ... |
| \( \chi^2/\nu \) | 191/270 | 178/220 |
| \( N_{\text{H}} \) (10^22 H atoms cm \(^{-2}\)) | 1.803 \( \pm \) 0.044 | 0.372 \( \pm \) 0.055 |

* The errors are 68% confidence for one interesting parameter (\( \Delta \chi^2 = 1.0 \)).

* Fit includes data from the PCA, HEXTE, and OSSE.

* Fixed.

\( ^{a} \) This is the unabsorbed 2.5–20 keV component flux.
When the post-transition spectrum is fitted with a disk-blackbody plus power-law model, the fit is formally acceptable ($\chi^2/\nu = 187/221$). However, as for the pre-transition spectrum, we tried to improve the fit using a reflection component and a Gaussian line. As shown in Table 2, we find that including a reflection component improves the fit only slightly. Adding a Gaussian iron line improves the fit significantly, and we find that this component is necessary at more than 99% significance. Further evidence that the reflection component is not necessary to fit the post-transition spectrum comes from the fact that adding a reflection component to a model consisting of a disk-blackbody, a Gaussian iron line, and a power law does not improve the fit. As shown in Table 3, similar results are obtained using the Comptonization model instead of the disk-blackbody. Specifically, we find that the Gaussian iron line is necessary at more than 99% significance, but there is no evidence for reflection.

The fit parameters for the models 1 and 2 fits to the post-transition spectrum are shown in Tables 4 and 5, respectively. For the post-transition fits described above, all three Gaussian iron line fit parameters were left as free parameters. However, we find that for both model 1 and 2, the post-transition values found for $E_{\text{line}}$ and $\sigma_{\text{line}}$ are consistent with those found for the pre-transition fits. Thus the post-transition fits were recalculated after fixing $E_{\text{line}}$ and $\sigma_{\text{line}}$ to the pre-transition values in order to improve the constraints on the other parameters. For both models, we
find that the equivalent width of the iron line is lower for the post-transition spectrum than for the pre-transition. The equivalent width is 38 eV for model 1 and 192 eV for model 2. We also place upper limits on the covering fraction for reflection. Using model 1, we find that the 95% confidence upper limit on \( \Omega/2\pi \) is 0.067, while using model 2 the 95% confidence upper limit is 0.15. Thus reflection is significantly less important in the post-transition spectrum compared to the pre-transition spectrum. Another significant difference between the spectra, which will be discussed further below, is that the power-law index for the post-transition spectrum is considerably harder than for the pre-transition spectrum. The post-transition spectrum, fitted using model 1, is shown in Figure 4b.

ASCA observations of GRO J1655—40 give column densities ranging from \( N_H = 4.4 \times 10^{21} \) cm\(^{-2}\) (Nagase et al. 1994) to \( N_H = 8.9 \times 10^{21} \) cm\(^{-2}\) (Zhang et al. 1997a). Fitting the pre-transition spectrum with model 1 gives a column density significantly above this range (see Table 4). To check this result, we fixed \( N_H \) to the value found by Zhang et al. (1997a) and refitted the pre-transition spectrum using model 1. With \( N_H \) fixed, we find that \( \chi^2/\nu = 293/272 \), which is significantly worse than the fit with \( N_H \) free. The column density for the pre-transition spectrum may be higher than the previous values found using ASCA and higher than we find for the post-transition spectrum because of absorption due to material near the source. When model 2 is used, the column densities for the pre-transition and post-transition spectra are consistent (see Table 5). Although the values of \( N_H \) found using model 2 are above the range of values found using ASCA, the ASCA column densities are derived using different spectral models.

From ASCA spectra, Ueda et al. (1998) recently reported a detection of iron absorption lines for GRO J1655—40. In the 1995 August ASCA spectrum, Ueda et al. (1998) find a K\( \alpha \) absorption line due to highly ionized iron (Fe xxvi) with an equivalent width of 25\(^{+13}_{-13} \) eV. Ueda et al. (1998) derives a 1 \( \sigma \) upper limit on the width of the iron line of 150 eV. To look for this absorption line in our spectra, we added a Gaussian at a fixed energy of 6.98 keV and a fixed width of 150 eV to model 1 and refitted the pre-transition and post-transition spectra. An absorption line is not detected for either the pre-transition or post-transition spectrum. For the pre-transition spectrum, we find a 95% confidence upper limit on the equivalent width of 24.4 eV, and for the

**TABLE 5**

**GRO J1655—40 SPECTRAL FITS WITH MODEL 2**

| Parameter          | Pre-transition | Post-transition |
|--------------------|----------------|-----------------|
| **Comptonization** |                |                 |
| \( kT \) (keV)     | 2.66\(^{+0.42}_{-0.31} \) | 1.26\(^{+0.021}_{-0.026} \) |
| \( \tau \)         | 7.64\(^{+0.73}_{-0.63} \) | 14.11\(^{+0.022}_{-0.007} \) |
| Flux (photons cm\(^{-2}\) s\(^{-1}\) \( \nu \)) | 5.7\(^{+1.4}_{-1.9} \) | 6.7\(^{+3.3}_{-1.3} \) |
| **Power Law**      |                |                 |
| Flux (photons cm\(^{-2}\) s\(^{-1}\) \( \nu \)) | 2.69\(^{+0.023}_{-0.036} \) | 2.41\(^{+0.010}_{-0.014} \) |
| EW (eV)            | 5.7\(^{+1.4}_{-1.9} \) | 2.05\(^{+0.059}_{-0.053} \) |
| **Gaussian**       |                |                 |
| \( E_{\text{line}} \) (keV) | 6.21\(^{+0.31}_{-0.33} \) | 6.21\(^{+0.023}_{-0.026} \) |
| \( \sigma_{\text{line}} \) (keV) | 1.69\(^{+0.16}_{-0.15} \) | 1.69\(^{+0.023}_{-0.026} \) |
| \( N_{\text{line}} \) (photons cm\(^{-2}\) s\(^{-1}\)) | 0.203\(^{+0.054}_{-0.038} \) | 0.077\(^{+0.013}_{-0.016} \) |
| EW (eV)            | 319            | 192             |
| **Reflection**     |                |                 |
| \( \Omega/2\pi \)  | 0.85\(^{+0.08}_{-0.23} \) | 0.0\(^{+0.08}_{-0.23} \) |
| \( r \)            | 69.5           |                 |
| \( \chi^2/\nu \)   | 171/269        | 159/219         |
| \( N_H(10^{22} \text{ H atoms cm}^{-2}) \) | 2.99\(^{+0.18}_{-0.16} \) | 2.57\(^{+0.30}_{-0.36} \) |

\(^a\) The errors are 68% confidence for one interesting parameter (\( \Delta \chi^2 = 1.0 \)).

\(^b\) Fit includes data from the PCA, HEXTE, and OSSE.

\(^c\) Fit includes data from the PCA and HEXTE.

\(^d\) This is the unabsorbed 2.5–20 keV component flux.

\(^e\) Fixed.
post-transition spectrum, we find a 95% confidence upper limit on the equivalent width of 26.5 eV. Although we do not detect an iron absorption line, our data does not allow us to rule out the absorption line observed by Ueda et al. (1998). However, it appears that the structure between 6 and 8 keV in our spectrum is considerably different from that observed by ASCA, since we observe an ion emission line that was not detected by ASCA.

5. DISCUSSION

For GRO J1655 — 40, the change from the pre-transition state to the post-transition state represents a significant change in the luminosity; hereafter the pre-transition state will be referred to as the high-luminosity state, and the post-transition state will be referred to as the intermediate-luminosity state. The unabsorbed luminosity for the high-luminosity state is $1.7 \times 10^{38}$ erg s$^{-1}$ (1.5 keV—2 MeV), assuming a distance of 3.2 kpc and isotropic emission, corresponding to 18% of the Eddington luminosity ($L_{\text{Edd}}$) for a 7 $M_\odot$ compact object (Orosz & Bailyn 1997). For the intermediate-luminosity state, the unabsorbed luminosity is $9.2 \times 10^{37}$ erg s$^{-1}$ (1.5 keV—2 MeV), which is 10% of $L_{\text{Edd}}$. Figure 5 shows the high-luminosity and intermediate-luminosity states' spectra along with a previously reported GRO J1655 — 40 broadband spectrum based on simultaneous 1995 August ASCA and BATSE observations (Zhang et al. 1997a). The intermediate-luminosity state spectrum is very similar to the 1995 August spectrum, while the shape of the high-luminosity state spectrum is much different.

For the power-law component, the intermediate-luminosity state photon index is considerably harder than the high-luminosity state photon index ($\alpha = 2.415 \pm 0.011$ compared to $\alpha = 2.722^{+0.037}_{-0.028}$). Also, the 2.5 keV—2 MeV flux of the power-law component is about a factor of 3 higher for the high-luminosity state than the intermediate-luminosity state. The differences in the power-law component between the high- and intermediate-luminosity state are consistent with the trend previously reported for GRO J1655 — 40 by Wilson et al. (1995) from BATSE measurements and by Grove et al. (1998) from OSSE measurements: that the spectral index softens as the intensity of the hard component increases.

In Table 1 we show that a power law with a spectral cutoff provides a better fit to the high-luminosity spectrum than a power law with no cutoff. The measured cutoff energy is $1086^{+125}_{-145}$ keV, and we find that the 95% confidence lower limit to the cutoff energy is 829 keV. Chakrabarti & Titarchuk (1995) have suggested that the power-law component may be caused by the Comptonization of soft photons from the accretion disk by material being radially accreted onto the black hole. This mechanism, known as bulk-motion Comptonization, is different from thermal Comptonization models, since it relies on the radial velocity of the infalling material to produce hard X-rays. The bulk-motion Comptonization model predicts a power-law spectrum of $E \lesssim 511$ keV and a sharp cutoff above this energy rather than a gradual, exponential cutoff. For the 115 hr OSSE integration, GRO J1655 — 40 is detected in an energy band from 513 keV to 2 MeV at a flux of $1.0 \times 10^{-9}$ ergs cm$^{-2}$ s$^{-1}$ and a confidence level of 99.977% (3.5 $\sigma$). We do not see a sharp cutoff near 511 keV. However, this cutoff may apply only in the Schwartchild geometry and not to bulk-motion Comptonization near a maximally rotating black hole.

To explain the GRO J1655 — 40 hard component, it is necessary to explain the lack of a cutoff in the spectrum below about 800 keV and the correlation between flux and power-law index. The flux-index correlation is commonly seen in AGNs (Grandi et al. 1992; Guainazzi et al. 1996), and it has been explained by inverse Compton scattering of soft photons on hot electrons with a thermal velocity distribution (Haardt, Maraschi, & Ghisellini 1997) or on electrons with a nonthermal velocity distribution (Yaqoob 1992). However, it should be noted that the typical photon index observed for AGNs is significantly harder than for GRO J1655 — 40 and that the high-energy cutoffs observed in AGNs are well below $m_e c^2$.

While the behavior of the power-law component does not depend on whether model 1 or 2 is used, the change in the soft component does depend on which model is used. As shown in Table 4, if model 1 is used, the flux of the disk-blackbody component is about a factor of 2 higher in the intermediate-luminosity state than in the high-luminosity state. If model 2 is used, the flux of the Comptonization component does not change significantly between states (see Table 5).

Although models 1 and 2 provide acceptable fits to both spectra, they are based on somewhat different physical assumptions. The main difference is that, while model 1 assumes that we are seeing blackbody emission from an optically thick disk directly, model 2 assumes that we see the soft emission from the disk only after it is Comptonized, possibly in an accretion disk corona. The Comptonization parameters we give in Table 5 assume a disk geometry for the Comptonization region. In the following, we first discuss the results assuming model 1 correctly describes the physical situation, and then we will discuss the results assuming the physical situation is correctly described by model 2.
5.1. Model 1 Implications

From analysis of the 1995 August GRO J1655 — 40 spectrum, which is similar to our intermediate-luminosity state spectrum, Zhang et al. (1997b) suggest that the black hole in GRO J1655 — 40 is rotating at about 93% of its maximal rate in the prograde direction (i.e., $a_\ast = 0.93$). We define $a_\ast = a/r_g$, where $a = J/M_c$, $r_g = GM/c^2$, and $M$ and $J$ are the mass and the angular momentum of the black hole, respectively. In their calculation, Zhang et al. (1997b) assume that the disk extends to the marginally stable orbit, $r_{ns}$. When model 1 is used to fit the GRO J1655 — 40 spectra, the disk-blackbody parameters imply that the inner edge of the disk is closer to the compact object in the high-luminosity state than in the intermediate-luminosity state. This may indicate that the inner edge of the disk in the intermediate-luminosity state does not reach $r_{ns}$. Also, since $r_{ns}$ decreases with increasing black hole rotation rate, our spectral results for the high-luminosity state imply that $a_\ast > 0.93$. The inner disk radius ($R_{in}$) can be derived from the disk-blackbody normalizations ($N_{BB}$) using equation (1). For the high-luminosity state spectrum, if $i = 69.5^\circ$, then $R_{in} = 10.9 \pm 2.6$ km. The value of $r_{ns}$ for a maximally rotating 7 $M_\odot$ black hole is 10.4 km, so that the value of $R_{in}$ is consistent with a maximally rotating black hole (Bardeen, Press, & Teukolsky 1972).

We have considered the possibility that $R_{in}$ is being underestimated, because the inclination angle of the disk close to the black hole is larger than 69.5°. Although the binary inclination angle has been measured by Orosz & Bailyn (1997) to very high accuracy, $i = 69.50 \pm 0.08$ degrees, it is possible that the inclination angle of the accretion disk close to the black hole is different from the binary inclination. If we assume that the inclination of the radio jets, 85° (Hjellming & Rupen 1995), gives the disk inclination close to the black hole, then the implied value of $R_{in}$ increases to 21.9 $\pm$ 5.2 km. Assuming that $r_{ns} = R_{in}$ gives $a_\ast = 0.93 \pm 0.08$.

Timing analysis has been performed for both of the RXTE observations of GRO J1655 — 40 discussed in this paper, and a complete description of this analysis will be published separately (Remillard et al. 1998). A quasi-periodic oscillation (QPO) at 300 Hz was observed when the source was in the high-luminosity state but not when it was in the intermediate-luminosity state. The presence of the 300 Hz QPO in the high-luminosity state may signify an important difference between the states. While at present there is no consensus regarding the physical mechanism generating the QPO, most of the suggested mechanisms require an accretion disk terminated near the marginally stable orbit. If 300 Hz corresponds to an orbital period around a 7 $M_\odot$ black hole (Remillard et al. 1997), then the implied radius of the orbit is 64 km. This radius (64 km) is considerably more than the value of $R_{in}$ implied by our spectral results, which probably indicates that 300 Hz is not equal to the frequency of a particle orbit at the inner edge of the disk. Other mechanisms have been suggested that may be able to explain the presence of the 300 Hz QPO in GRO J1655 — 40. The QPO in GRO J1655 — 40 may be caused by $g$-mode oscillations of the accretion disk (Nowak & Wagoner 1992) or by frame-dragging (Cui et al. 1998a). Frame-dragging may be able to produce QPOs by causing precession of the inner region of the accretion disk (Stella & Vietri 1998). For both of these mechanisms, the predicted QPO frequency depends on the black hole rotation rate. Coincidentally, in both cases, a value of $a_\ast = 0.95$ is derived when the models are applied to GRO J1655 — 40 (Zhang et al. 1997b; Cui et al. 1998a). The high black hole rotation rate is in rough agreement with our spectral results.

5.2. Model 2 Implications

The physical picture for model 2 is that the soft emission from the disk is Comptonized in a plasma near the disk. The high-luminosity state fit parameters imply a plasma with a temperature of $2.66^{+0.42}_{-0.21}$ keV and an optical depth of $7.64^{+0.75}_{-0.63}$, which corresponds to a Comptonization $\gamma$-parameter of 1.22. After the transition to the intermediate-luminosity state, the plasma temperature decreases to $1.260^{+0.021}_{-0.026}$ keV, and the optical depth increases to $14.11^{+1.02}_{-0.70}$, which corresponds to $\gamma = 1.96$. If the emission responsible for the iron line is Comptonized, then, as we observe in the GRO J1655 — 40 spectrum, a broad iron line is expected (Sunyaev & Titarchuk 1980). From the expression $\Delta E = (E^2/\tau^2)/m_e c^2$ (Sunyaev & Titarchuk 1980), the width of the high-luminosity state iron line gives $\tau \sim 5.0$. This is in reasonably good agreement with the value for $\tau$ found from the Comptonization fit parameters for the high-luminosity state. The centroid energy of the iron line is expected to be redshifted because of the recoil of the electron, since the plasma temperature of the Comptonizing region is less than the energy of the line. Our measured centroid energy is consistent with a redshifted 6.4 keV iron line, but the uncertainty is too large to make a meaningful redshift estimate. There is some precedent for broad iron lines in black hole candidates. The mass of the compact object in 4U 1543 — 47 is between 2.5 and 7.5 $M_\odot$ (Orosz et al. 1998), indicating that it is likely that this source contains a black hole. During EXOSAT observations of 4U 1543 — 47, an iron line was detected with $\sigma_{line} = 1.15$ keV and $E_{line} = 5.93$ keV (van der Woerd, White, & Kahn 1989). Assuming that Comptonization is responsible for the broadening of the iron line, an optical depth between 4 and 5 is implied.

6. Conclusions

We find that the GRO J1655 — 40 energy spectrum can change significantly on relatively short timescales. The luminosity changes from about 18% of $L_{Edd}$ to about 10% of $L_{Edd}$, and the photon index of the power-law component changes from $2.72^{+0.03}_{-0.05}$ to $2.415 \pm 0.011$ between the high- and intermediate-luminosity states. Comparing the high- and intermediate-luminosity—state spectra shows a positive correlation between the power-law index and the flux of the power-law component, which is consistent with the previously reported trend. Models to explain the hard spectral component are constrained by this trend and the fact that power law extends to 800 keV without a cutoff. In the high-luminosity state, we find evidence for a broad iron line and a reflection component. In the intermediate-luminosity state, there is evidence for a broad iron line. The fact that a 300 Hz QPO is observed only in the high-luminosity state should provide additional information about the system.

We regard the models we use for the soft component as approximations to the actual physical system. Global models of the accretion flow, which account for all of the accretion physics, are necessary. Specifically, for GRO J1655 — 40, it seems that the large changes in the power-law
flux observed between the high- and intermediate-luminosity states must be related to the simultaneous changes in the soft component. Construction of a physical model that generates all the observed emission components and reproduces the correlation between the various spectral components will be necessary for reliable extraction of the physical parameters of accreting compact objects.

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