GRO J1655–40: EARLY STAGES OF THE 2005 OUTBURST

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ABSTRACT

The black hole X-ray binary transient GRO J1655–40 underwent an outburst beginning in early 2005. We present the results of our multiwavelength observational campaign to study the early outburst spectral and temporal evolution, which combines data from X-ray (RXTE and INTEGRAL), radio (VLA), and optical (ROTSE and SMARTS) instruments. During the reported period, the source left quiescence and went through four major accreting black hole states: low-hard, hard intermediate, soft intermediate, and high-soft. We investigated dipping behavior in the RXTE band and compare our results to the 1996–1997 case, when the source was predominantly in the high-soft state, finding significant differences. We consider the evolution of the low-frequency quasi-periodic oscillations and find that the frequency strongly correlates with the spectral characteristics, before shutting off prior to the transition to the high-soft state. We model the broadband high-energy spectrum in the context of empirical models, as well as more physically motivated thermal and bulk motion Comptonization and Compton reflection models. RXTE and INTEGRAL data together support a statistically significant high-energy cutoff in the energy spectrum at ≃100–200 keV during the low-hard state. The RXTE data alone also show it very significantly during the transition, but not in the high-soft state spectra. We consider radio, optical, and X-ray connections in the context of possible synchrotron and synchrotron self-Compton origins of X-ray emission in low-hard and intermediate states. In this outburst of GRO J1655–40, the radio flux does not rise strongly with the X-ray flux.

Subject headings: accretion, accretion disks — black hole physics — gamma rays: observations — stars: individual (GRO J1655–40)

Online material: color figures

1. INTRODUCTION

X-ray novae, also known as soft X-ray transients, are a subclass of the low-mass X-ray binaries (LMXBs) for which prolonged periods of quiescence are occasionally interrupted by dramatic, accretion-powered optical, UV, and X-ray outbursts (Chen et al. 1997; McClintock & Remillard 2006). A majority of these binaries have been determined to contain compact primaries with mass functions exceeding the nominal 3 $M_\odot$ limit for neutron stars; indeed, most of the known stellar-mass black holes are associated with this class of objects. These outbursts are frequently accompanied by radio emission, which is generally associated with collimated outflows. The radio emission is transient in nature, and a wide range of behavior has been documented.

Conventional classification of black hole (BH) spectral states includes five states, namely, the quiescent state, low-hard state (LHS), intermediate state (IS), high-soft (or thermally dominant) state (HSS), and very high (or steep power law) state. McClintock & Remillard (2006) recently reviewed these states. They advocate the names in parentheses, as being more accurately descriptive. However, we follow tradition in the use of the abbreviation HSS.

The LHS energy spectrum is dominated by a hard (spectral index 1.4–1.6) power law. A thermal component is either very small or not seen at all. Strong variability (up to 40%) in the form of band-limited noise is observed in this state, often accompanied by quasi-periodic oscillations (QPOs) seen in the Fourier power density spectrum (PDS) as narrow peaks. Stable radio emission with a flat spectrum has been observed during the LHSs of a set of BH X-ray sources. It has been associated with steady relativistic jets and outflows (Gallo et al. 2003). BH transients are usually observed in the LHS when their luminosity is less than 5% of the Eddington luminosity. The HSS, in contrast to the LHS, is dominated by a thermal component with a characteristic temperature of ≃0.5–1.0 keV, which is attributed to bright emission from an optically thick accretion disk. In the HSS the power-law index is steeper (>2.0), and variability is suppressed to not more than several percent [which is dominated by red noise, i.e., $P(f) \sim 1/f$]. The LHS and the HSS are the best observed and documented BH states. During transitions between them, a BH source enters an IS, where the source may exhibit diverse behavior with mixed LHS and HSS properties. Homan & Belloni (2005) considered the phenomenology of the IS in detail and introduced two substates, which they call the hard intermediate state (HIMS) and the soft intermediate state (SIMS; see also Belloni 2006; Belloni et al. 2006). For the HIMS the energy spectrum is softer than in the LHS, and the thermal component is more pronounced. The PDS is still dominated by band-limited noise with characteristic frequencies higher than those observed for the LHS. Radio emission is also observed in the HIMS, but with a slightly steeper spectrum. In the SIMS the disk component starts to dominate the energy spectrum and further softening is observed. The total rms variability drops sharply. The PDS is a sum of band-limited and power-law components or is sometimes even more complicated in shape. This subdivision of IS into HIMS and SIMS is consistent with the behavior of GRO J1655–40 during the hard-to-soft
transition that we observed, so we adopt this terminology when we want to refer to a particular intermediate substrate. In our data we identify LHS, HIMS, SIMS, and HSS periods.

The X-ray binary GRO J1655−40 is a well-known example of a BH X-ray transient, having undergone several major outbursts within the last 12 years. It was discovered by the BATSE instrument on board the Compton Gamma-Ray Observatory in mid-1994 (Zhang et al. 1994; Harmon et al. 1995). The secondary star being relatively bright, the binary parameters are exceptionally well determined among LMXBs. The most recent optical photometry of Green et al. (2001) led to a BH mass estimate of 6.3 ± 0.5 M☉. Hjellming & Rutan (1995) inferred a distance to GRO J1655−40 of 3.2 ± 0.2 kpc from radio jet analysis. Mirabel et al. (2002) discussed in detail different methods of distance estimates and concluded that for GRO J1655−40 the upper limit is 3.5 kpc and the lower limit is 0.9 kpc.

The light curve of the discovery outburst was irregular, in the sense that it deviated substantially from the often seen fast-rise exponential decay form (Che et al. 1997). It was instead characterized by several distinct peaks, with subsequent sporadic, lower amplitude outburst activity continuing into 1995. These initial events were correlated with the contemporaneous radio observations. Most notable was the discovery of radio jets, which exhibited apparent superluminal motion (Harmon et al. 1995; Hjellming & Rutan 1995; Tingay et al. 1995). The later, low-amplitude events, however, were apparently not associated with additional plasma ejections leading to the type of radio emission initially interpreted as apparent superluminal motion (Harmon et al. 1995; Hjellming & Rutan 1995; Mirabel et al. 2002) discussed in detail different methods of distance estimates and concluded that for GRO J1655−40 the upper limit is 3.5 kpc and the lower limit is 0.9 kpc.

In this paper we report on the results of our multiwavelength observational campaign, beginning with the outburst detection and ending on 2005 March 16 (MJD 53,445), after the source completed the hard-to-soft state transition. The data are described in § 2. Our analysis of the INTEGRAL and RXTE observations is presented in § 3. This includes light-curve analysis, as well as our spectral model fitting. We discuss dipping behavior in § 3.3. Interpretation and conclusion are presented in § 4.

2. OBSERVATIONS AND DATA ANALYSIS

Our data combine programs of ToO, as well as publicly available observations from RXTE, INTEGRAL, the VLA, the Robotic Optical Transient Search Experiment (ROTSE), and the Small and Moderate Aperture Research Telescope System (SMARTS). Below, we provide details for each data set.

2.1. RXTE

The RXTE campaign of pointed observations of the new outburst from GRO J1655−40 started on 2005 February 21 (MJD 53,422) and provided data on an almost daily basis. Observations were taken under RXTE proposals 90058, 90428, 90404, 90704, and 91702. In addition to Standard PCA data modes, high time and energy resolution data were collected. For low and moderate count rates an Event mode with ~125 µs time resolution in 256 energy channels was collected. For high source fluxes the high-resolution data were provided by two Single Bit modes covering PCA channels 0–13 and 14–25, respectively, along with an Event mode for counts registered in channels above 36.

Data from the deep monitoring proposal 91702 were made publicly available, and Homan et al. (2005a, 2005b, 2005c) also posted energy and power spectra, as well as light curves. These observations began on 2005 March 7 (MJD 53,436), shortly after the source started the transition from the LHS. We have used data from some of these observations to put the LHS and the IS in the context of the developing outburst. We reduced and analyzed them ourselves, together with the previous data, for a uniform treatment.

The data reduction and analysis was performed using FTOOLS 5.3 software. For spectral analysis we use the PCA Standard2 data mode and the Standard Archive HEXTE mode. Standard deadtime correction was applied to all spectra. Spectra were modeled using the XSPEC 11.0 astrophysical fitting package. We used 3.0–30.0 keV and 18.0–300.0 keV energy intervals for PCA and HEXTE data, respectively. We added a 1% systematic error to the data during our spectral analysis. The uncertainties on spectral model parameters were calculated using 1σ confidence intervals. For Fourier analysis we use high time resolution PCA data modes, combining counts from different modes to get a signal from the entire PCA energy range. After rebinning the data to obtain the Nyquist frequency value of 1024 Hz, we calculate individual PDSs for consecutive 128 s intervals and averaged them for each RXTE orbit. For timing analysis we utilize our own IDL library routines.

7 See http://www.astro.yale.edu/smarts.
2.2. INTEGRAL

An INTEGRAL ToO observation of GRO J1655–40, previously approved as part of the General Program (see Winkler et al. 2003), was performed between MJD 53,425.21 and 53,427.60. The observations consist of a series of dither pointings lasting between 58 and 146 minutes each. In our case a total of 49 pointings were included in the analysis. Data from the INTEGRAL hard X-ray instruments IBIS/ISGRI and SPI, as well as from the 3–35 keV X-ray monitor JEM-X, were used in our analysis. All three instruments use the coded-mask imaging technique. Data reduction was performed using the standard OSA 5.0 analysis software package available from the INTEGRAL Science Data Centre (Courvoisier et al. 2003). Note that because of the nature of coded-mask imaging, the whole sky image taken by the instrument has to be included in the analysis, as all sources in the field of view contribute to the background (Caroli et al. 1987). The total exposure time of 178 ks is the ISGRI effective on-source time. This value is approximately the same for the spectrograph SPI (186 ks), but the JEM-X monitor (17.5 ks) covers a much smaller sky area. Thus, in the case of dithering observations, the source is not always in the field of view of the monitor.

In order to achieve more complete time coverage, we added IBIS/ISGRI data of GRO J1655–40 provided by the INTEGRAL Galactic bulge monitoring program (PI: E. Kuulkers). Within this program GRO J1655–40 was observed once every orbit (i.e., every 3 days) for 12.6 ks (Kuulkers et al. 2006).

The analysis of the ISGRI data is based on a cross-correlation procedure between the recorded image on the detector plane and a decoding array derived from the mask pattern (Goldwurm et al. 2003). Imaging analysis led to a detection significance of 93, 5, and 20σ, for the ISGRI (20–200 keV), SPI (20–200 keV), and JEM-X (3–35 keV) data, respectively. The INTEGRAL IBIS/ISGRI 20–40 keV significance map is shown in Figure 1. No nearby point sources are detected closer than 1′ (RXTE collimator FWHM) and brighter than 1 mcrab above 20 keV.

2.3. VLA

The radio data are presented in Table 1. The data were taken with the VLA in its B configuration, using standard continuum modes to obtain two 50 MHz intermediate-frequency pairs of right- and left-circular polarization, for a total bandwidth of 200 MHz. Flux densities were derived from 3C 286, which was also observed during most runs. Phases were calibrated using interleaved observations of strong nearby point sources. The data were reduced using the 31DECO4 version of the National Radio Astronomy Observatory (NRAO) AIPS package (e.g., Bridle & Greisen 1994).

Observations were made at 1425, 4860, 8460, and 22460 MHz. No extension is seen in any of the images, for which the typical resolution was 5.1′′ × 1.2′′ (8.46 GHz/ν), oriented roughly north-south. Gaussian fits to each image showed no convincing elongations, with typical upper limits of 0.8′′–1′′ at 8.46 GHz. The 1σ flux uncertainties are listed in column (6) of Table 1. From these values it is seen that absolute flux calibration is accurate to typically 10%–15%. Upper limits in the figures are the sum of the nominal flux density at the position of the source, plus 3 times the rms noise.

While the observed position of the source shifts significantly from epoch to epoch, probably this is simply due to variable atmospheric effects at the low elevations required at the VLA to observe such a southern source. Indeed, shifts of similar magnitude are seen between the different observing frequencies on a given day, and other sources in the field at 1.4 and 4.9 GHz also move around from epoch to epoch. Minimizing the effects of outliers and removing two observations that were clearly unreliable, we obtain a mean (J2000.0) position in arcseconds of

\[
\alpha = 16^h54^m00.139^s \pm 0.008, \quad \delta = -39^\circ50'44.7'' \pm 0.2''
\]

where the error bars were derived after adding 0.5′′ in quadrature to the statistical errors found for each individual image, as required to give an average L1 deviation of 1σ from this mean. Within the errors this position is consistent with the optical position that Bailyn et al. (1995) found in 1994. The measurements are not accurate enough to detect the proper motion of 5 mas yr\(^{-1}\) derived by Mirabel et al. (2002).

2.4. Optical Data

We use data from ROTSE (Akerlof et al. 2003) for the optical light curve (Smith 2005). ROTSE images are unfiltered, calibrated to the USNO A2.0 R band, and then converted to flux units via numerical integration of the CCD response function.

From SMARTS we use the data obtained by Buxton et al. (2005) in the B, V, I, J, and K bands with the ANDICAM instrument on the SMARTS 1.3 m telescope at Cerro Tololo Inter-American Observatory on February 21 (MJD 53,422.3–53,422.4). Optical magnitudes at quiescence were taken from Green et al. (2001). The latter’s uncertainty in period would imply the photometric phase was within about 0.1 of 0.97.

3. RESULTS

3.1. Multifrequency Evolution

The radio, optical, and X-ray light curves are shown in Figure 2. In Figure 3 we plot several interesting properties of the source that we derived from the data. The rising stage of the outburst consists of three distinct phases. Specifically, after an initial 5 day rise from ~8.5 to ~17 mcrab (2–10 keV), the source dwelt for
In Figure 4 we show representative energy and power spectra for each interval.

### 3.1.1. Low-Hard State (MJD 53,418–53,435)

The LHS stage lasted from the detection on February 17 (MJD 53,418) through March 6 (MJD 53,435). After an initial 10 day rise with no detected spectral change, the source entered a rather stable period that lasted for approximately 5 days, with roughly constant X-ray flux and hardness. The X-ray spectrum is well fit by a power law of index $\approx 1.5$, while less than 10% of the

\begin{table}[h!]
\centering
\caption{Radio Observations}
\begin{tabular}{cccccc}
\hline
Date & MJD & $\nu$ & $S_\nu$ & $\int S_\nu dt$ & $dt$ \\
(1) & (2) & (MHz) & ($\text{mJy beam}^{-1}$) & ($\text{mJy}$) & (minutes) \\
\hline
2005 Feb 23 & 53,424,5786 & 1425.0 & 1.63 & 1.73 & 0.11 & 21.3 \\
2005 Feb 27 & 53,428,5184 & 1425.0 & 1.90 & 1.83 & 0.17 & 8.9 \\
2005 Mar 4 & 53,433,5088 & 1425.0 & 1.15 & 1.18 & 0.22 & 4.5 \\
2005 Mar 6 & 53,435,5149 & 1425.0 & 1.78 & 1.84 & 0.20 & 7.7 \\
2005 Mar 9 & 53,438,5695 & 1425.0 & 1.51 & 1.67 & 0.19 & 7.7 \\
2005 Mar 10 & 53,439,4845 & 1425.0 & 1.41 & 1.12 & 0.18 & 7.7 \\
2005 Jan 4 & 53,374,6404 & 4860.1 & [−0.03] & ... & 0.13 & 8.4 \\
2005 Feb 20 & 53,421,5750 & 4860.1 & 1.34 & 1.39 & 0.12 & 5.7 \\
2005 Feb 23 & 53,425,5891 & 4860.1 & 1.59 & 1.46 & 0.07 & 18.5 \\
2005 Feb 24 & 53,425,5089 & 4860.1 & 1.49 & 1.52 & 0.11 & 10.9 \\
2005 Mar 4 & 53,432,5149 & 4860.1 & 1.89 & 2.01 & 0.10 & 6.6 \\
2005 Mar 6 & 53,435,5149 & 4860.1 & 1.32 & 1.28 & 0.11 & 7.6 \\
2005 Mar 9 & 53,438,5786 & 4860.1 & 1.36 & 1.22 & 0.10 & 7.9 \\
2005 Mar 10 & 53,439,4845 & 4860.1 & 1.08 & 0.86 & 0.11 & 7.7 \\
2005 Mar 16 & 53,445,5854 & 4860.1 & 1.80 & 1.73 & 0.07 & 25.2 \\
2005 Feb 20 & 53,421,5813 & 8460.1 & 0.8 & 1.3 & 0.15 & 5.6 \\
2005 Feb 23 & 53,424,5933 & 8460.1 & 1.41 & 1.48 & 0.08 & 11.5 \\
2005 Feb 27 & 53,428,5402 & 8460.1 & 1.57 & 1.56 & 0.05 & 15.8 \\
2005 Mar 4 & 53,433,5241 & 8460.1 & 1.53 & 1.50 & 0.09 & 6.3 \\
2005 Mar 6 & 53,435,5341 & 8460.1 & 1.14 & 1.31 & 0.13 & 6.7 \\
2005 Mar 9 & 53,438,5886 & 8460.1 & 1.10 & 1.02 & 0.10 & 6.7 \\
2005 Mar 10 & 53,439,5019 & 8460.1 & 0.80 & 0.71 & 0.09 & 6.1 \\
2005 Mar 14 & 53,443,5210 & 8460.1 & [0.15] & ... & 0.13 & 5.6 \\
2005 Feb 27 & 53,428,5294 & 22460.1 & [0.27] & ... & 0.30 & 8.5 \\
2005 Mar 9 & 53,438,5971 & 22460.1 & [0.56] & ... & 0.48 & 3.9 \\
2005 Mar 10 & 53,439,5109 & 22460.1 & [−0.31] & ... & 0.30 & 3.9 \\
2005 Mar 16 & 53,445,5871 & 22460.1 & ... & ... & ... & 3.2 \\
\hline
\end{tabular}
\end{table}

~4 days in the LHS. On March 4 (MJD 53,433) the flux started rising again, accompanied by a gradually softening spectrum, indicating that the source entered the hard-to-soft transition phase. We follow the spectrum evolution for a month, beginning from the start of RXTE pointed observations, when the source was in the low-hard state (LHS), to the point where the source completes the transition to the high-soft state (HSS). We divided the period of interest into the three intervals, according to the source state. We also subdivide the IS into two substates according to the Homan & Belloni (2005) classification.

Notes.— Radio flux densities of GRO J1655–40, as observed with the Very Large Array (VLA). All observations represent continuous scans and were taken in the VLA B configuration, unless otherwise noted. Fast switching was employed throughout. Phase calibrators were 1626–298 at 1425.0 MHz, 1607–335 at 4860.1 MHz, and 1650–297 at 22460.1 MHz. The flux density scale was set by contemporaneous observations of 3C 286, unless otherwise noted.

- **a** UT date at midpoint of observations, before flagging.
- **b** Modified Julian Day at midpoint of observations (before flagging): MJD = JD − 2,400,000.5.
- **c** Mean observing frequency. This is the arithmetic mean of two independently tuned 50 MHz bands, observed simultaneously in both circular polarizations.
- **d** Peak flux density. Unbracketed numbers represent the observed peak, after removing a planar background fit to the surrounding pixels; see text. Bracketed numbers represent nondetections and give the value at the known position of the source.
- **e** Integrated flux density (for detections only), after removing a planar background fit to the neighboring pixels, as described in the text. This represents the sum of the believable emission from the source. Any difference between this and the peak flux density reflects uncertainties in the images.
- **f** Root mean square (rms) noise in the image, as determined from a Gaussian fit to the distribution of flux densities in a region without any (known) emission. This represents a lower limit on the uncertainty in the flux density, and a comparison of the peak flux density to this rms noise gives a reasonable signal-to-noise ratio for judging the statistical reliability of a detection.
- **g** Time on-source, before flagging. Unless noted otherwise, this is a continuous observation, centered on the listed MJD, apart from interruptions for phase calibration.
- **h** There were no contemporaneous observations of 3C 286 during this run. Instead, the flux density scale was set by linearly interpolating the flux density of the phase calibrator from surrounding observations. This additional error thus introduced is not significant for the data reported here.
- **i** Observations at 1425, 4860, and 8460 MHz on 2005 Feb 27 were made up of two sets of scans, separated by about an hour. The values reported here result from co-adding all of these data; the two sets of scans in all cases agree within 1σ with the averages reported here.

The LHS stage lasted from the detection on February 17 (MJD 53,418) through March 6 (MJD 53,435). After an initial 10 day rise with no detected spectral change, the source entered a rather stable period that lasted for approximately 5 days, with roughly constant X-ray flux and hardness. The X-ray spectrum is well fit by a power law of index $\approx 1.5$, while less than 10% of the
emission is in a thermal component. The PDS is represented by a broken power law typical of the LHS (also known as band-limited noise). The lower frequency part is usually flat, while after a brake the slope is 1\text{–}1.5. The low-frequency QPO appears above this continuum as a narrow peak (see Fig. 4a). The luminosity at this juncture was about 0.5\% Eddington (for the distance of 3.2 kpc and the mass of 6.3 \(M_\odot\)). The flat-spectrum radio source is roughly steady at \(\sim 1.5\) mJy, Buxton et al. (2005) and Torres et al. (2005) concluded that the optical magnitudes were within the amplitude range of quiescent ellipsoidal variations of the companion. The ephemeris during this time is uncertain by 0.27 days. The ISGRI light curve comprises both the INTEGRAL bulge scan and our proposal data. The PCA flux is given as detected in the proportional counter unit (PCU) 2.

\[\text{Fig. 2.—Top to bottom: Radio (VLA), R-band optical (SMARTS and ROTSE), X-ray (RXTE and INTEGRAL), and HXTE light curves. To obtain R-band flux from SMARTS data, we linearly interpolated the data from Buxton et al. (2005). Vertical lines indicate the approximate dates when the source changes its spectral state. The solid horizontal line on the panel with the optical data corresponds to the quiescent ROTSE flux. The dashed lines show the minimum and maximum of quiescent ellipsoidal variations of the companion. The ephemeris during this time is uncertain by 0.27 days. The ISGRI light curve comprises both the INTEGRAL bulge scan and our proposal data. The PCA flux is given as detected in the proportional counter unit (PCU) 2.}\]

\[\text{Fig. 3.—Top to bottom: Quantities derived from the data: spectral index, calculated from radio data using pairs of observational points (1.425 and 4.860 GHz \[\text{[red]}\] and 4.860 and 8.460 GHz \[\text{[black]}\]); PCA hardness ratio; X-ray spectral index obtained from the POWER LAW+BLACKBODY model fit to the PCA data; and QPO frequency and its rms variability. Important changes occur in the source behavior around MJD 53,440, when the radio flux drops effectively to zero (see Fig. 2), while the QPO amplitude drops abruptly, to disappear 2 days later. Vertical lines mark the boundaries between spectral states that are discussed in the text.}\]

\[kT \sim 0.2\text{ eV}.\] In Figure 5 we plot the total observed optical fluxes, the average quiescent levels, and outburst fluxes calculated as the total minus the average quiescent flux. The low temperature of this component suggests that the outer accretion disk is its origin. Using the average quiescent fluxes should give an underestimate of the fluxes and an overestimate of \(kT\), if the phase was indeed near the shallower \(V\)-band minimum.

3.1.2. Intermediate State (MJD 53,435–53,442)

3.1.2.1. Hard Intermediate State

The period from MJD 53,435 through 53,440 is marked by a roughly exponential rise in the X-ray flux, with the X-rays gradually softening. The 2–10 keV flux rises by over an order of magnitude during this interval. Also a rise in the optical flux was observed with ROTSE. Power-law fits to the X-ray and optical data sets give characteristic rise times of 3–4 days, with the rise being slowest in the optical and hard X-rays. The rise of the 2–10 keV flux reflects the gradual softening of the source, seen also in the power-law index \(\Gamma\) (Fig. 2). The radio data are sparse, but they indicate a turnover in the source flux and a steepening of the spectrum. There is no sign of the factor of \(\sim 5\) increase like that of the simple \(S_\nu \propto \nu^{-\gamma}\) radio–to–X-ray scaling observed for some BH transients rising to the HSS transition (Gallo et al. 2003).

For this outburst of GRO J1655–40, at least, the radio emission is quenched relatively early in the evolution. The high-energy cutoff in the X-ray spectrum during the IS becomes much more pronounced, before disappearing in the HSS. The same cutoff phenomenology (i.e., marginal in the LHS, strong in the IS, and absent in the HSS) was also observed in 4U 1543–47.
Kalemci et al. (2005) and XTE J1550–564 (Tomsick et al. 2001). The timing properties evolve rapidly during this stage. The QPO frequency rises from 0.5 to 2 Hz. However, the overall shape of the PDS remains similar to that of the LHS, with increasing characteristic frequencies (Fig. 4b).

3.1.2.2. Soft Intermediate State

A remarkably quick change in the properties of the source emission occurred between MJD 53,439 and 53,440 in all wavelengths. First, the radio emission disappears and the optical flux levels off. A sharp rise in X-ray luminosity, by a factor of 2 from 0.02 to 0.04$L_{\text{Edd}}$, occurs (see also Fig. 6), which is in agreement with the luminosity for a rise-phase hard-to-soft state transition in BH sources given by Meyer-Hofmeister et al. (2005). The spectrum abruptly softens from photon index 1.7 to 2.1. The total variability drops below 10%. A red-noise-like continuum feature appears above the broken power law (Fig. 4c). During the next RXTE observation on MJD 53,441, the source flux recedes to the level consistent with the exponential rise of the HIMS, and we have the last detection of the low-frequency QPO, at an increased frequency of around 17 Hz. After that, the flux starts to level off, and the source enters the HSS.

3.1.3. High-Soft State (MJD 53,442 and Beyond)

The final stage in this early evolution is the HSS, from MJD $\sim$53,442 through the end of the period considered here. This is characterized by the rapid and somewhat jittery softening of the X-ray spectrum, the disappearance of the radio emission, and a relatively stable optical flux. The energy spectrum is dominated by a thermal disk component, and no low-frequency QPO or band-limited noise component is detected (Fig. 4d).

Brocksopp et al. (2006) identified MJD 53,440 (March 11) as an approximate date of the LHS-HSS transition. This conclusion is based on the behavior of the Swift BAT light curve. Our data sampling and broadband energy coverage resolve distinct HIMS and SIMS between the LHS and the HSS. The HIMS-SIMS transition occurs on 53,440; our analysis is thus consistent with the Brocksopp et al. (2006) estimate.

3.2. Spectral Modeling of the X-Ray Data

3.2.1. LHS Broadband X-Ray Spectrum

During the 2.4 days of our INTEGRAL observation, the spectrum did not change noticeably. There were RXTE observations at the beginning, midpoint, and end of this period. We have used the sum of these observations (RXTE observation IDs 90058-1604-00, 90428-01-01-00, 90058-16-05-00, and 90428-01-01-01) to construct the composite spectrum shown on Figure 7. The spectrum is approximately an absorbed power law, with photon index
≈1.4, typical of LHS spectra of accreting BHs (χ² = 1.86 for 344 degrees of freedom [dof]). But the fit is significantly improved with more complex models. The results for the continuum are presented in Table 2. We applied several different models that are often used to capture the properties of a thermal disk and a Comptonizing corona. Here we summarize the results for the composite spectrum, but we discuss the models further in the following section, in the context of the evolution of the spectrum as the outburst develops. In §4.6 we discuss the alternative of synchrotron and synchrotron self-Compton mechanisms for the emission in the LHS.

The fit is greatly improved with addition of a blackbody component, an emission line due to iron, and a high-energy exponential cutoff (χ² = 1.16 for 338 dof). A narrow line at 6.33 ± 0.16 has an equivalent width (EW) of 97 eV. Comptonization and reflection models both give fits of similar quality, and the χ² value is not grounds for favoring one over the other. The XSPEC bulk motion Comptonization (BMC) model, named for its applicability to the case of Comptonization of seed photons in plasma with high-velocity bulk motion, employs a self-consistent convolution of a Planck function with a Green’s function to account for Compton scattering. This should best represent the physical situation when soft disk photons are upscattered in a hot corona. We also fit the data with the model representing Comptonization in a thermal cloud (the COMPTT model in XSPEC). In this model the effective electron temperature kT_e is the fit parameter. The best-fit value of 37 keV is less than what one would expect from the cutoff, i.e., kT_e = E_{fold}/2 (this approximate relation follows from the comparison of the analytical model for unsaturated Comptonization [Sunyaev & Titarchuk 1980] with the results of Monte Carlo simulations [Titarchuk 1994]). However, the difference is qualitatively understandable, considering the error bars on E_{fold} and the effects on the COMPTT spectrum of the optical depth. The model of reflection of a power-law source from a cool disk (PEXRAV in XSPEC implemented by Magdziarz & Zdziarski 1995) also provides an acceptable fit to the combined spectrum.

The spectrum emitted by a part of the accretion disk not covered by the corona is thermal and ideally should be represented by either a blackbody shape with kT_{bol} ≈ 0.5–1.0 keV or an integral over temperatures for the multicolor disk model (MCD and DISKBB in XSPEC; Mitsuda et al. 1984). However, we found that the real situation is more complicated, especially in the HSS, where we need two thermal components to fit the spectrum (see discussion below).

The BMC model in XSPEC was developed as a generic Comptonization model by Titarchuk et al. (1997) to treat Compton upscattering of low-frequency photons in a converging flow of thermal plasma onto a BH. It can describe the production of a steep power-law component in the BH HSS. Soft seed photons in the BMC model are assumed to have a pure blackbody energy distribution with temperature kT_e. A fraction A/(1 + A) of the input spectrum is Comptonized in the hot corona, while the other

### Table 2

| Parameter | Value |
|-----------|-------|
| (POWER LAW + BLACKBODY) × CUTOFF* |       |
| \(\Gamma\) | 1.35 ± 0.03 |
| \(kT_{bol}\) | 1.00 ± 0.05 keV |
| \(E_{fold}\) | 181.1 ± 0.3 keV |
| \(\chi^2_{(\text{red})}\) | 1.16 (338) |

**BMC × CUTOFF**

| Parameter | Value |
|-----------|-------|
| \(\Gamma\) | 1.36 ± 0.04 |
| \(kT_{bol}\) | 0.71 ± 0.07 keV |
| \(f\) | 1.82 ± 0.03 keV |
| \(E_{fold}\) | 194.1 ± 7.9 keV |
| \(\chi^2_{(\text{red})}\) | 1.16 (338) |

**COMPTT + BLACKBODY**

| Parameter | Value |
|-----------|-------|
| \(kT_{bol}\) | 0.60 ± 0.06 keV |
| \(kT_{e}\) | 37.3 keV |
| \(\tau\) | 4.4 ± 0.2 |
| \(\chi^2_{(\text{red})}\) | 1.23 (338) |

**PEXRAV + DISKBB) × CUTOFF**

| Parameter | Value |
|-----------|-------|
| \(\Gamma\) | 1.35 ± 0.06 |
| \(R\) | 0.12 ± 0.10 |
| \(T_{bol}\) | 1.49 ± 0.06 keV |
| \(E_{fold}\) | 196.4 ± 4.8 keV |
| \(\chi^2_{(\text{red})}\) | 1.15 (337) |

Note.—In addition to the listed components each fit also includes a narrow Gaussian with energy 6.4 keV to model the iron line.

* For CUTOFF, the XSPEC multiplicative model HIGHECUT was used with fixed \(E_{bol} = 0\).
part leaves the system unchanged. However, in the lower $\dot{M}$, LHS configuration, reduced Compton cooling of the ambient plasma leads to electron temperatures much higher than that of the converging inflow. The thermal source is then not seen, and scattering from the higher temperature plasma dominates the observed emission. The BMC model is applicable in the general case of Comptonization when the bulk and thermal electron motion are included. This model can be used provided the electron temperatures involved are higher than the mean photon energy. At higher photon energies, the spectrum exhibits a cutoff at 100–200 keV, indicating that the photon energies are on the order of the electron thermal energy, and the cutoff multiplying the BMC model represents the effect the electron energy distribution would have. This model is convenient for describing the evolution of a BH through different states and is based on a theoretical picture.

The reflection model PEXRAV along with DISKBB can also describe the spectral changes of BHs, although it does not itself provide an underlying rationale for the changes that occur. In principle, effects of reflection should be added to the BMC model. However, the models are too much alike in functional form for the fits to the data to separate the contributions to the continuum.

To examine the time evolution of the energy spectrum, we analyzed RXTE PCA data from the beginning of the outburst until 2005 March 15 (MJD 53,444), when the source has completed the LHS-to-HSS transition. Following the above discussion, we fit the data to BMC+GAUSSIAN and PEXRAV+DISKBB+GAUSSIAN models.

The results are given in Figures 8 and 9 for the BMC and PEXRAV model, respectively. In fitting the PEXRAV model, we let the photon index and reflection factor change freely and fixed the abundance of iron and heavy elements at 1.0. The spectral index given by fits to the BMC model rises from the value of 1.4 for the LHS to 1.8 during the state transition and reaches 2.2 for the HSS, while the PEXRAV model results in power-law spectral indices 0.2–0.4 higher. The disk component is insignificant during the LHS and the entire IS for the PEXRAV model. For both models a Gaussian with the centroid energy of ~6.5 keV was included to model an iron line. For the LHS the iron line is mostly narrow ($\sigma \leq 1$ keV). The EW of the line is $\leq 200$ eV for BMC and $\leq 100$ keV for PEXRAV, both within the range expected from the cold-disk reflection. However, after the transition, the Gaussian derived in the fits becomes much broader, with $\sigma 1.5–2.0$ keV, and the EW of the feature grows by a factor of 3–5. Reflected iron lines have been calculated for a variety of conditions. EWs this high, and also very broadened lines features, can be obtained (e.g., Dabrowski & Lasenby 2001; Martocchia et al. 2000; Ballantyne et al. 2002), but only for special, extreme conditions of position of the source relative to a maximally rotating BH or high overabundance of iron. High iron line EWs were obtained in models of reprocessing in a wind from the central source (Laming & Titarchuk 2004), but this model did not yield large widths and, besides, is not thought to be applicable to the HSS. Alternatively, the high width of the Gaussian may indicate that the model component, initially intended to model a narrow spectral line, is trying instead to mimic some part of the broader underlying continuum not included in the model. Our analysis also shows that a pure BMC model (with additional GAUSSIAN fixed at 6.5 keV for an iron line) during the HSS is not statistically acceptable ($\chi^2/N_{\text{dof}} \approx 2.0$). We attribute this behavior to the fact that the accretion disk emission is not well described by a pure blackbody. We attempted to resolve this issue by replacing the unscattered blackbody component of the BMC component with a multicolor disk component (i.e., DISKBB). The quality of the fit was slightly improved; however, the behavior of the Gaussian remained the same, with very high widths and EWs required.

Second, we replaced the Gaussian in the BMC+GAUSSIAN model by a simple blackbody shape. The model fit was dramatically improved. We obtained the following properties of this alternative model. The temperature of the new soft thermal component is approximately half of the BMC’s seed photon temperature. The

| Detector     | $N_{\text{DET}}/N_{\text{PCA}}$ |
|--------------|----------------------------------|
| ISGRI        | 0.87 ± 0.03                      |
| SPI          | 1.05 ± 0.12                      |
| JEM-X        | 0.59 ± 0.05                      |
| **RXTE**     |                                  |
| HEXTE A      | 0.81 ± 0.02                      |
| HEXTE B      | 0.80 ± 0.02                      |

Note.—The normalization of the incident flux required by each instrument is given relative to that required by the RXTE PCA.

FIG. 8.—Outburst spectral evolution: BMC model component parameters. The model describes the data well in the LHS and HIMS, while in the HSS the fit is not satisfactory.
temperature of the seed photons, in turn, slightly increased, compensating for the linelike continuum residual. The narrow iron line is only needed, for the LHS and the IS (see Fig. 10). For the HSS, a good fit is achieved with BMC and soft blackbody only. Interestingly, the narrow iron emission line, with an energy consistent with fluorescence, increases in flux, along with the increase in the nonthermal spectrum, which might excite it from the disk material and disappears when the spectrum becomes steep and dominated by the thermal emission. A soft thermal component might be emission from radii of the accretion disk larger than the source of seed photons for the BMC. Its temperature $kT_{bb}$ is consistently lower than the temperature of incoming photons for the BMC component. In fact, the relation $kT_{bb}/C_{24}^0:5kT_{BMC}$ holds throughout the entire time period of interest. The soft blackbody component is barely significant for the LHS, and its contribution grows toward the HSS. This fact is consistent with the conventional scenario in which the size of the corona shrinks as the accretion rate increases and the source enters the state transition. The size of the uncovered disk increases, allowing for a greater contribution of the soft component. The temperature of this component grows as it approaches the HSS, which is also in agreement with the implied picture, as inner parts of the disk should supply the hotter photons. From the same reasoning, it is clear why the multicolor disk does not work in this case. In the DISKBB model, the normalizations of the inner and outer parts of the disk are locked together by integrating over the radius with the $r^{-3/4}$ temperature profile. In the real situation, a part of the radiation from the inner component is taken away by Comptonization. This imbalance is not accounted for the XSPEC DISKBB model.

Recently, several models that take into account effects not handled correctly in the DISKBB model have been developed. The XSPEC KERRBB model (Li et al. 2005) is the most inclusive. We tested this model on the observation during the HSS on MJD 53,443 (March 14, RXTE Observation ID: 91702-01-03-00). We fit the PCA spectrum with a model consisting of KERRBB+BMC with the thermal component of the BMC model suppressed (by fixing the log $A$ parameter at 7.0). For the KERRBB component we fixed the inclination angle at 70°, the distance at 3.2 kpc, and the BH mass at 6.3 $M_\odot$ and $f_{\text{col}} = 1.65$. We also fixed the parameter $eta$ at zero, which corresponds to a standard Keplerian disk with zero torque at the inner boundary. The best fit gives $\chi^2_{\text{red}} = 2.18$. Addition of a Gaussian with the energy fixed at 6.5 keV results in an acceptable $\chi^2_{\text{red}} = 0.98$. The EW of the feature is a reasonable 210 eV. The best-fit value of the specific angular momentum of the BH is 0.53 ± 0.01, somewhat less than the 0.65–0.75 found by Shafee et al. (2006) with the same $f_{\text{col}}$ for the RXTE 1997 observations. More detailed modeling would be needed to determine whether the line width of 1.2 keV could be accommodated in terms of Doppler shifts and reddening. KERRBB can handle corrections to the basic disk picture that are known to be needed and these seem to be on the order of the discrepancy.

![Fig. 9.—Outburst spectral evolution: PEXRAV model component parameters. In the text the difficulty of explaining the iron line is discussed.](image9.png)

![Fig. 10.—Iron line properties inferred from the BMC+BLACKBODY fits. The line is narrow. The 3 σ upper limit on the flux in the HSS corresponds to an upper limit on the EW of only 9 eV.](image10.png)
between the data and the simple disk approximations. It needs to be used to separate line emission, reflection, and possible structure of disks, as well as to determine the angular momentum of the BH.

3.3. Intensity Dips

In the 1996–1997 outbursts, when the source was in the HSS, a variety of dips were observed (Kuulkers et al. 2000, hereafter K00; Kuulkers et al. 1998; also see Tanaka et al. [2003] regarding dips during the 1994 outburst). In the case of our current campaign, the source remained for the most part in the LHS. Nonetheless, examination of the 16 s standard-mode light-curve data also revealed dips. This is a little surprising, as the dips are widely believed to be associated with partial occultation of the central disk region by the accretion stream or by more complex geometric accretion configurations. The LHS emission, on the other hand, consists of Comptonized photons, presumably scattered from plasma ambient to the disk. There have been arguments that this scattering media is large compared to the inner disk region, where the thermal X-radiation emanates (e.g., Hua et al. 1999). That would seem to make the mechanism that produces the HSS dips less effective for the LHS case. In any case, K00 find that for the case of the 1996–1997 outburst, the HSS dips occupy a relatively narrow, approximately Gaussian distribution when plotted as a function of phase. Specifically, they find that the dips are approximately described by a Gaussian centered on phase 0.785 with a \( \sigma \) of 0.046.

To study the dipping behavior in our data, we examined the entire 16 s standard-mode light curve, which of course has gaps; see Figure 11 for examples. For the ephemeris calculation we used the zero spectroscopic phase 2, 449, 839.0763 \( \pm 0.0055 \) JD of Orosz & Bailyn (1997) and the 2.62191 \( \pm 0.00020 \) day binary period of Green et al. (2001), which is calculated consistently with the Orosz & Bailyn (1997) data. We shifted by 0.75 phase to obtain an equivalent photometric phase zero of 2, 449, 841.0427 \( \pm 0.0055 \). The \( 2 \times 10^{-4} \) day uncertainty in the period, combined in quadrature with the uncertainty in the phase-zero determination, translates to an uncertainty of 0.11 in phase in our data.

We identified instances where the intensity dropped by \( \sim 50\% \) or more, relative to the local average, in at least one bin, at a significance level of at least 5 \( \sigma \). We found 46 dips in total, 28 in the LHS, 10 in the IS, and 8 in the HSS. We then sorted the dips into orbital phase bins using the ephemeris information as described. This resulted in the distribution shown in Figure 12. Note that, while our dips are still relatively narrowly distributed in phase, they are centered on phase 0.5, with substantially more dispersion.
the phase 0.785 at a
find no dips within the narrow distribution of K00 centered on
(spectrum for the interval between the dips is plotted in green. The change in spec-
trum during dips is accounted for by variations in the absorption column $N_H$ [See the
electronic edition of the Journal for a color version of this figure.]

We do not have as large a statistical sample as K00 (46 vs. 65).

We note that Tanaka et al. (2003) reported unusual dipping
behavior during an Advanced Satellite for Cosmology and Astro-
physics (ASCA) observation of GRO J1655—40 in 1994. In that
case, the dip profile was significantly broader, with a width of
several hours, while ours are typically several 16 s bins wide.
They reported that it occurred in the HSS when the secondary
was on the far side of the BH and that their spectral analysis was
consistent with pure photoelectric absorption provides an ade-
quate explanation (see Fig. 13). In addition, we examined public
data spanning approximately from MJD 53,445 to 53,460, i.e.,
after the onset of the HSS transition. We find a dearth of dipping
activity in that portion of the data.

We observe rising radio emission during the LHS, a declining
radio flux in the HIMS, and its turnoff in the SIMS. The radio
data from MJD 53,433 are unique in showing a pronounced peak
at 5 GHz. X-ray binaries in the LHS typically produce a very
stable, flat-spectrum radio source, as seen here in the plateau stage.
A 5 GHz peak is highly unusual and suggests an expanding, opti-
cally thick source, typical of the early stages of jet ejection.

We have studied multifrequency data spanning the early stage
of the 2005 outburst of GRO J1655—40. The empirical behavior
observed includes spectral transition from the LHS through the
HIMS and SIMS to the HSS, accompanied by the expected rise
in the thermal component and a steepening of the power-law spec-
tral index; QPO appearance and its frequency rise throughout the
LHS and the intermediate states and its turnoff on entering the
HSS; a high-energy cutoff in the LHS and IS; and intensity dips
during the LHS, which are consistent with photoelectric absorp-
tion and correlated differently with orbital phase than the HSS
dips observed by K00 for the 1996–1997 outburst.

We observe rising radio emission during the LHS, a declining
radio flux in the HIMS, and its turnoff in the SIMS. The radio
data from MJD 53,433 are unique in showing a pronounced peak
at 5 GHz. X-ray binaries in the LHS typically produce a very
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A 5 GHz peak is highly unusual and suggests an expanding, opti-
cally thick source, typical of the early stages of jet ejection.

While the latter is not convincing on any given day, the radio spec-
trum is consistently flatter (harder) during the plateau stage and
steadier (softer) during the exponential rise. Taken together with
the decoupling between the X-ray and the radio flux, it seems
likely that the radio emission here has a different physical origin
from that during the plateau. The plateau seems much like the
standard LHS, in the ratio of X-ray to radio fluxes, and the flat
radio spectrum, suggestive of a compact core. The radio emis-
sion during the HIMS may instead be a more extended jet, al-
though it is far from obvious why that jet should be so stable (in
flux density and spectrum).

Currently, there are two competing theories to explain the or-
igin of the X-ray power-law spectrum in BH sources. In the first,
the canonical model, the power-law slope is produced by Com-
tonization of the soft disk photons in the extended optically thin
corona, located above the accretion disk. But Markoff et al. (2003
and references therein) argue that the power-law component in the
LHS can be attributed to a combination of the optically thin high-
energy tail of the synchrotron spectrum from the radio jet base and
synchrotron self-Compton emission adding the highest en-
ergy component. In the framework of the model, the synchrotron
jet base subsumes the role of the corona in Comptonization
models (e.g., Nowak et al. 2005; Markoff et al. 2005). However,
the lack of radio and X-ray correlation in our data makes it dif-
cult in the case of GRO J1655—40 to associate the base of a
compact jet with the Compton-scattering corona that creates the
power-law X-ray emission. Gallo et al. (2003) found evidence

![Fig. 13.—Absorption nature of the dips observed in the hard state. Spectra
shown in black and red are extracted during dips A1 and A2 (Fig. 11a), while the
spectrum for the interval between the dips is plotted in green. The change in spec-
trum during dips is accounted for by variations in the absorption column $N_H$.
][See the electronic edition of the Journal for a color version of this figure.]

![Fig. 14.—Energy fluxes in spectral components for fits to the POWER-
LAW+BB model. The power-law flux is calculated for 2–20 keV. The blackbody
flux is the bolometric flux inferred from the normalization of the component. An
apparent jump occurs in both fluxes around MJD 53,441. After that, the black-
body component continues to rise, while the power-law flux starts to decline.
]
for radio and X-ray correlation for several sources, although they also saw that in some cases the radio emission was quenched at some point in the X-ray rise. It is possible that the radio-emitting region is larger than the X-ray corona and not dominated by the X-ray emitting part. This would mean that the situation may be more complex. Recently, the jet base model has been subjected to other observational challenges. Maccarone (2006) argued that if the LHS spectrum is due to the jet, which is radiatively inefficient in nature, the transition to the HSS should be accompanied by a sharp change in luminosity. While we observe a rather quick rise in the thermal component during the SIMS around MJD 53,440 (see Fig. 14), the corresponding power-law flux does not drop, but jumps up, together with the black-body component, before it starts to decay smoothly. Overall, our analysis does not validate the jet base model; however, some presence of synchrotron and synchrotron self-Compton emission cannot be ruled out.

It is apparent that the system is far from a steady state configuration during the LHS and the state transition. Most probably, the accretion disk, which is quiescent prior to the outburst, gradually gets involved in outburst activity by some instability propagating either from the innermost parts of the disk to the outside or from the outer disk to the inside (e.g., Cannizzo et al. 1995). Information from the QPO phenomena can give an important clue toward distinguishing between the two possible directions of the heat front propagation. For example, in the case of shock wave or front propagation in the disk, one could expect the X-ray flux to be modulated at the frequency of the disk Keplerian rotation at the radius of the shock location. If this process is indeed responsible for the observed flux oscillations, then the outward propagation scenario is not correct, and the shock is propagating inward from a larger radius, as advocated by Chakrabarti et al. (2005). However, there is evidence for a closer coupling of the QPO phenomena with the power-law component than with the disk component, so that the accretion disk shock wave oscillation model for the oscillations is not compelling. QPO rms variability is found to increase with energy (see van der Klis 1995 and references therein). Vignarca et al. (2003) found a close correlation of power-law spectral index with QPO centroid frequency for BH sources GRS 1915+105, GRO J1655−40, XTE J1550−564, and 4U 1630−47. For GRO J1655−40, Vignarca et al. used data from the 1996−1997 outburst. Figure 15 shows that in the 2005 outburst rise the spectral index was correlated with QPO frequency above about 0.8 Hz. Both the power-law and the black-body (seed photon source) fluxes were correlated with the frequency, while the radio flux is not (see Fig. 16). In the BMC model, the power-law flux and the blackbody are related. However, the spectral index is independent of QPO until a significant rise in flux has occurred. Qualitatively, these correlations are consistent with the BMC model and do not exhibit the same indications of a jet base model shown in some other sources by Migliari et al. (2005). There are other models that could relate this QPO frequency to the fluxes, such as that of the occultation of the power-law component by a precessing disk ring (Schnittman et al. 2006). The dynamical consistency of such a ring and the connection to the spectrum of the disk component should be further investigated.

The location of dips has been discussed in terms of the impact of the accretion stream on the disk (e.g., Bisikalo et al. 2005).
The location may be a function of the rate of accretion flow. The structure of the dips may put limits on the size of the emission region, as has been done for neutron star low-mass binaries (e.g., Church 2001). Detailed study of this is beyond the scope of this paper.

In summary, the 2005 outburst of GRO J1655–40 was observed intensely with X-ray instruments, with very interesting and diagnostic results. During the early phases, there was good radio coverage and less thorough, but nevertheless useful, optical coverage. The X-ray data allow spectral fits to generic Comptonization and power law plus reflection models with a cutoff, multicolored disk, and fluorescence. If the corona is really the base of a relativistic outflow, the radio flux does not exhibit the proportionality to the X-ray flux that is seen in some other BH sources, or a simple anticorrelation of the flux between the power-law and the disk components of the spectrum. Low-frequency QPOs seem to suggest that their origin, presumably at an interface between an optically thick and a coronal component, is moving inward in radius, as the frequency is positively correlated with the luminosity in the power law and the luminosity in a disk component (and inversely with its inner radius), while the radio flux decreases as the QPO reaches its maximum. The spectra of the power-law component are limited by a high-energy cutoff, although we are unable to study this aspect in detail. While our study in this paper extends only to when the HSS began, the observations that followed will address many other points, including the degree of similarity of the decay of this transient to its rise.

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