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"CANONICAL" BLACK HOLE STATES IN THE SUPERLUMINAL SOURCE GRO J1655−40

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ABSTRACT

We analyze *Rossi X-Ray Timing Explorer* (*RXTE*/PCA) observations of the black hole candidate and Galactic superluminal source GRO J1655−40 during its recent outburst. We show that during its decay to quiescence, GRO J1655−40 goes through the high, intermediate, and low state (and that at the beginning of its decay it might have even shown signatures of a very high state), just like other black hole candidates. This is the first time that such a transition is observed in a Galactic superluminal source. We discuss what are the implications of these results on the hypothesis that the spin of the black hole in superluminal sources is much higher than in other black hole candidates.

Subject headings: accretion, accretion disks — binaries: close — black hole physics — stars: individual (GRO J1655−40) — X-rays: stars

1. INTRODUCTION

Our understanding of low magnetic field accreting neutron stars and black hole candidates (BHCs) has greatly improved in recent years, and a general scenario has been proposed in which source properties are determined by basic parameters, such as accretion rate, compact object mass, and magnetic field (van der Klis 1994).

One of the keys to this unified scenario has been the successful use of simultaneous timing and energy spectral data to identify the different source states, both in neutron star and black hole systems. For BHCs, four states have been recognized: (1) the low state (LS) (Tananbaum et al. 1972; Oda et al. 1971), with a flat (photon index $\Gamma = 1.5$–2) power-law X-ray spectrum and strong (25%–50% rms) band-limited noise with a break frequency of 0.03–0.3 Hz; (2) an intermediate state (IS) (Méndez & van der Klis 1997; Belloni et al. 1997b), in which the 2–10 keV flux is a factor of ∼4 higher than in the LS, a soft component is present in the energy spectrum while the power-law component is softer than in the LS ($\Gamma = 2$–3), the power spectrum shows 6–8 Hz quasi-periodic oscillations (QPO), and the break frequency of the band-limited noise is in the range 1–10 Hz; (3) a high state (HS) (Tananbaum et al. 1972; Oda 1977), in which the 2–10 keV flux is an order of magnitude higher than in the LS owing to the presence of an ultra–soft X-ray spectral component with sometimes a $\Gamma = 2$–3 power-law tail, and a weak (few percent rms) flat power-law power spectrum; and (4) a very high state (VHS) (Miyamoto et al. 1991), characterized by high 2–20 keV X-ray luminosity (2–8 times higher than in the HS), an ultra–soft X-ray spectral component plus a ($\Gamma \sim 2.5$) power-law tail, strongly variable 1%–15% rms band-limited noise with a much higher cutoff frequency (1–10 Hz) than in the LS, and often 3–10 Hz QPO. Apart from the difference in 2–20 keV luminosity, the timing and spectral properties of the IS are quite similar to those of the VHS; the distinction comes from the fact that they are separated by a HS with very different properties. So far, the VHS has only been observed in GX 339−4 (Miyamoto et al. 1991) and GS 1124−68 (Ebisawa et al. 1994).

The order in which black hole transients in their decay, and the persistent BHCs, have been observed to move through these states and similarities to neutron star states strongly suggest that the accretion rate is highest in the VHS and decreases through the HS, IS, and LS (Miyamoto et al. 1991; van der Klis 1994; Méndez & van der Klis 1997; Belloni et al. 1997b).

So far, two remarkable BHCs, GRS 1915+105 and GRO J1655−40, have stood out from the others. They show relativistic ejections, resembling a small-scale analog to the jets observed in active galactic nuclei and quasars (Mirabel & Rodríguez 1994), and several other types of unique behavior (Morgan, Remillard, & Greiner 1997; Belloni et al. 1997a; Fender et al. 1997), but until now there was little evidence for any of the canonical black hole states described above.

GRO J1655−40 was discovered during an outburst in 1994, and since then it has shown irregular outburst activity (e.g., Zhang et al. 1997). The most recent X-ray event of this source started on 1996 April 25 (Remillard et al. 1996) and lasted for about one and a half years. Dynamical measurements suggest the compact star in GRO J1655−40 is a black hole, with a mass of $\sim 7\ M_\odot$ (Orosz & Bailyn 1997; van der Hooft et al. 1998). A few weeks after the 1994 X-ray outburst, radio jets were detected expanding at apparent superluminal velocities (Tingay et al. 1995; Hjellming & Rupen 1995).

Here we present an analysis of the properties of GRO J1655−40 during the decay from its latest X-ray outburst. We find for the first time in a superluminal source that GRO J1655−40 goes through the HS, IS, and LS just like other BHCs.

2. OBSERVATIONS AND DATA ANALYSIS

The Proportional Counting Array (PCA) on board the *Rossi X-Ray Timing Explorer* (*RXTE*) observed GRO J1655−40 regularly from 1997 March until September, when it faded into quiescence. We selected eight observations (see Table 1) that represent a good sample of its decay from a list of about 30 publicly available in this period, from ≳16, 500 PCA counts s^{-1} (2–60 keV) to quiescence (see Fig. 1).

In all cases data were collected in a high-time (and low-energy) resolution mode, simultaneously with a mode with 16 s time resolution in 129 energy channels, which covered the full PCA energy band. We divided the high-time resolution data in segments of 256 s and produced an average power density spectrum (PDS) per observation extending from 1/256

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TABLE 1

Power and X-Ray Spectral Parameters

Parameter	May 28	Jul 8	Jul 29	Aug 3	Aug 14	Aug 18	Aug 25	Aug 29
Time								
UTC Start	07:41	11:28	08:26	15:57	10:33	13:37	10:26	03:38
UTC End	10:11	15:35	09:27	16:08	11:22	14:35	11:25	04:03
Rate[a] (counts s^{-1})	16900	9100	4000	1800	1100	320	40	4
Power Spectra								
rms_{BLN}[b] (%)	4.7 ± 0.1	2.8 ± 0.1	1.8 ± 0.1	<2	15.6 ± 0.4	18.0 ± 0.8	<19	<84
α_1	0.93 ± 0.01	0.94 ± 0.01	1.00 ± 0.05	1[c]	−0.19 ± 0.03	−0.25 ± 0.10	1[c]	1[c]
α_2	1.70 ± 0.04	1.47 ± 0.06	…	…	1.41 ± 0.05	1.02 ± 0.03	…	…
ν_{break} (Hz)	3.12 ± 0.17	1.21 ± 0.17	…	…	1.34 ± 0.03	0.23 ± 0.02	…	…
rms_{QPO_1} (%)	…	…	…	…	9.8 ± 0.2	5.6 ± 0.5	…	…
FWHM (Hz)	…	…	…	…	0.63 ± 0.03	0.16 ± 0.03	…	…
ν (Hz)	…	…	…	…	6.46 ± 0.01	0.77 ± 0.01	…	…
rms_{QPO_2} (%)	…	…	…	…	13.2 ± 0.7	15.4 ± 2.6	…	…
FWHM (Hz)	…	…	…	…	10.9 ± 0.8	3.7 ± 0.5	…	…
ν (Hz)	…	…	…	…	9.3 ± 0.3	1.3 ± 0.4	…	…
χ^2/d.o.f.	380/336	334/336	342/338	89/95	397/330	288/330	379/367	274/277
Energy Spectra								
kT_{in} (keV)	$1.20^{+0.01}_{-0.01}$	$1.05^{+0.01}_{-0.01}$	$0.86^{+0.01}_{-0.01}$	$0.79^{+0.01}_{-0.01}$	$0.46^{+0.05}_{-0.04}$	$0.37^{+0.04}_{-0.04}$	$0.38^{+0.02}_{-0.05}$	…
R_{in}[d] (km)	23^{+1}_{-1}	24^{+1}_{-1}	26^{+1}_{-1}	26^{+1}_{-1}	29^{+3}_{-5}	27^{+2}_{-7}	18^{+12}_{-6}	…
Γ (photon index)	$2.49^{+0.06}_{-0.06}$	$2.01^{+0.01}_{-0.01}$	$2.38^{+0.12}_{-0.13}$	$2.18^{+0.19}_{-0.13}$	$2.07^{+0.01}_{-0.01}$	$1.77^{+0.02}_{-0.02}$	$2.12^{+0.05}_{-0.05}$	$3.04^{+0.51}_{-0.44}$
Flux[e]	42.70	24.64	11.75	7.24	2.28	0.58	0.09	<0.009
DBB Flux[e]	39.66	23.30	10.26	6.66	0.30	0.05	0.03	…
χ^2/dof	28/46	25/46	20/46	34/46	66/48	46/48	57/48	171/52

Notes.—N_H was kept fixed at 8.9×10^{21} cm^{-2} (Zhang et al. 1997). Quoted errors represent 1 σ single parameter confidence intervals. Upper limits 95%.

[a] 2–60 keV background subtracted count rate for five PCA detectors.

[b] 0.01–100 Hz fractional rms amplitude.

[c] The slope was kept fixed to estimate the upper limit.

[d] For a distance of 3.2 kpc (Hjellming & Rupen 1995) and an inclination of 70° (Orosz & Bailyn 1997; Van der Hooft et al. 1998).

[e] Unabsorbed flux in the 2–10 keV range, in units of 10^{-9} ergs cm^{-2} s^{-1}.

to 1024 Hz. We subtracted the Poisson noise and the Very Large Event window contribution (Zhang et al. 1995; Zhang 1995) from each PDS and renormalized them to fractional rms squared per Hertz (see van der Klis 1995). The results of the fits to these PDSs are shown in Table 1 and Figure 2.

On July 29 the PDS fitted a power law with an index of ~1. Before that, on May 28 and July 8, the PDSs were very similar to that of July 29; however, a single power law did not fit the data well, especially between 0.1 and 1 Hz. We fitted these PDSs using a broken power law, although a power law with an exponential cutoff or two Lorentzians and a power law (as shown in Fig. 2) fitted as well. On August 3 the source showed no evidence for variability in our power spectra, with an upper limit on the fractional rms amplitude consistent with that of July 29.

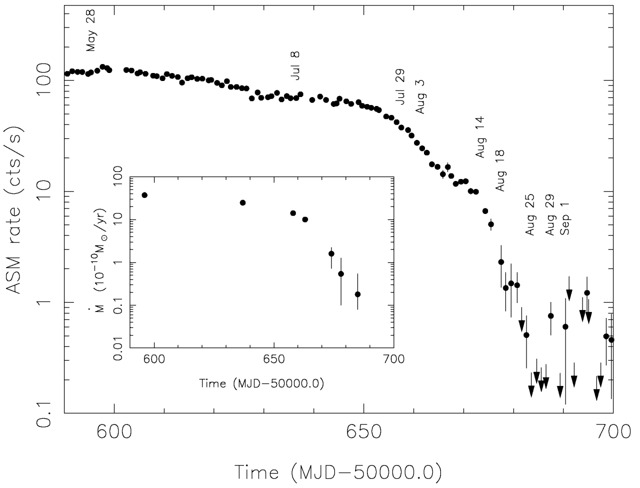

Fig. 1.—*RXTE* All-Sky Monitor light curve (1 day averages) of GRO J1655−40 from 1997 May 22 to 1997 September 9. Background rates were estimated based on the data points after this date, when the source is not detected by the ASM, and subtracted. (*Inset*) Inferred mass accretion rate for the observations of May 28, July 8 and 29, and August 3, 14, 18, and 25.

Between August 3 and 14 the PDS changed dramatically. On August 14 and 18 the PDS showed a strong band-limited noise component (BLN), a break at ≲1 Hz for which the frequency decreased as the count rate decreased, and a QPO feature moving from ~6.5 to ~0.8 Hz in correlation with the break of the BLN component. On August 25 and 29, at a much lower count rate, we could not measure any variability from the source, with upper limits that were consistent with the measurements of August 14 and 18. During the next PCA pointing, on September 1, we could not detect the source above the background level.

On August 14, while no other power spectral component showed a significant energy dependence, the amplitude of the 6 Hz QPO was lower at low energies, the rms amplitudes below and above 5 keV being 8.4% ± 0.3% and 11.3% ± 0.2%, respectively. On August 18 none of the fitted parameters depended significantly on energy.

We used the 16 s data to produce 2–30 keV energy spectra for each observation, which we then fitted with a model consisting of a disk blackbody (DBB) (Mitsuda et al. 1984) component plus a power law. We also added a Gaussian line plus an edge to fit the data around 7 keV, but the other parameters

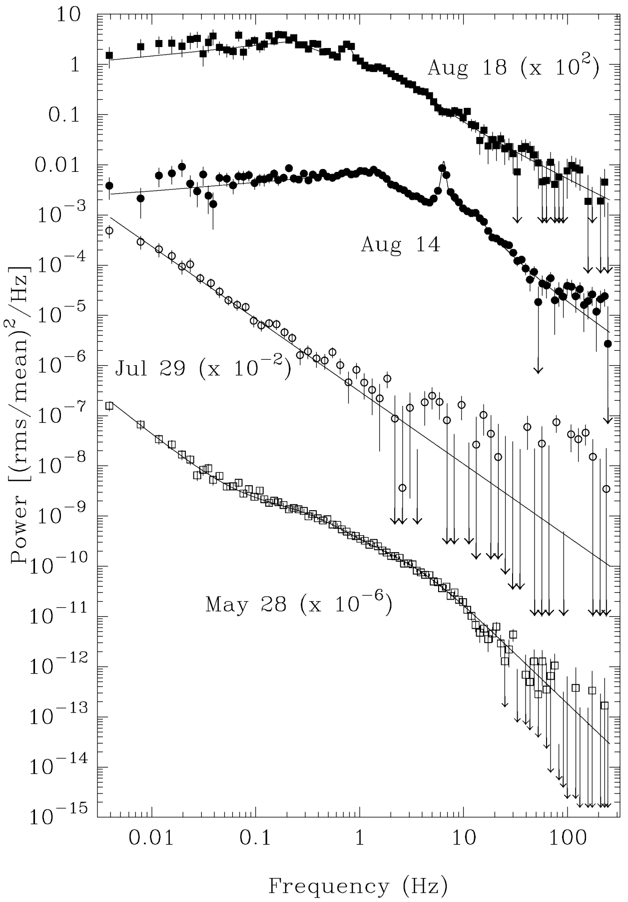

FIG. 2.—Power spectra of the observations of May 28, July 29, and August 14 and 18. The total fractional rms amplitudes are 4.7%, 1.8%, 15.6%, and 18.0%, respectively.

were not sensitive to the inclusion of these components. The interstellar absorption was kept fixed at 8.9×10^{21} cm^{-2} (Zhang et al. 1997). The best-fitting parameters are shown in Table 1.

During these observations, the temperature of the DBB decreased monotonically from ~1.2 to ~0.5 keV, but the derived inner radius of the disk did not change significantly. While the 2–10 keV flux decreased steadily during these observations, the relative contribution of the DBB component remained more or less constant at ~90% until August 3. Between August 3 and 14 this contribution dropped considerably; from August 14 onward it is $\lesssim$30%.

3. DISCUSSION

Our results show that the BHC and superluminal source GRO J1655−40 fits in with the general picture of BHC states described in § 1. During these observations the total 2–10 keV flux decayed by a factor of $\gtrsim$5000, the power-law component in the energy spectrum became harder, and the fractional contribution of the soft component to the total flux decreased by a factor of ~3. Simultaneously, the time variability increased by a factor of $\gtrsim$3, and the power spectrum developed a flat-topped band-limited noise component with a break frequency of ~0.1–1 Hz. All these changes, both in the energy and power spectra, indicate that GRO J1655−40 gradually passed through the HS, IS, and LS. This is the first time that such a transition was observed in a Galactic superluminal source, and it provides a unique opportunity to understand these sources in terms of canonical black hole states.

One of the characteristic properties of the band-limited noise component of a BHC in the LS and IS (and the VHS) is its variable break frequency, which anticorrelates with the rms amplitude measured at the break (Belloni & Hasinger 1990; Méndez & van der Klis 1997). The PDSs of August 14 and 18 show the same anticorrelation and fit in with previously observed sources (see Méndez & van der Klis 1997), supporting the conclusion that GRO J1655−40 behaves similarly to other BHCs.

On July 29 and August 3 the PDSs are consistent with those of a typical HS (van der Klis 1994), but on May 28 and July 8 they do not fit the canonical $\alpha \sim$ 1–1.5 single power-law shape. Because of the small rms amplitude that characterizes it, the PDS in the HS was not very well constrained in most previous observations. It may well be that the “unusual” shape of the PDSs on May 28 and July 8 (compared to what is expected in the HS) is the rule, but it is only the greater sensitivity of *RXTE* that allows us to measure it in more detail.

On May 28 the rms amplitude is also larger than was typically observed in the HS and comparable to that of the “anomalous” state reported by Kuulkers, van der Klis, & Parmar (1997) in 4U 1630−47. Perhaps this is an aspect of VHS behavior. The May 28 2–10 flux is $\gtrsim$60 times higher than in the LS (August 18) and 4 times higher than in the HS (July 29), and both the shape of the power spectrum and the total rms variability are very similar to those observed in GS 1124−68 on 1991 February 6, during its VHS (compare the power spectrum in Fig. 2 with that of Fig. 1 in Miyamoto et al. 1994). This would make GRO J1655−40 the third BHC (after GX 339−4 and GS 1124−68) to be observed in the VHS.

The application of the DBB plus power-law model to BHCs, previously strongly advocated on the basis of *Ginga* observations of classical BHCs (Tanaka & Lewin 1995), gains credence by the link provided by our observations between the superluminal and the classical BHCs. In GRS 1915+105, the application of this model leads to a very compelling explanation (Belloni et al. 1997a) for the large luminosity excursions in terms of rapid variations of the inner disk radius.

Using the values of R_{in} and T_{in} obtained from the spectral fits and the derived mass of the BHC (Orosz & Bailyn 1997; van der Hooft et al. 1998), we can infer the accretion rate of GRO J1655−40 during each observation (see Fig. 1, *inset*).

Despite the large decrease of $\dot{M}$, the DBB flux, and the total flux during this transition, the inner radius of the disk remained the same. The fitted values are consistent with a constant radius of 24.8 km. The same has been observed in GS 1124−68, GS 2000+25, GX 339−4, and LMC X-3 (Tanaka & Lewin 1995, and references therein), although in those cases the flux decreased by less than 2 orders of magnitude, not so dramatically as in GRO J1655−40. Tanaka (1992) interpreted this lack of change in R_{in} as a signature of the innermost stable orbit around a black hole. If we assume that the value of $R_{\mathrm{in}} = 24.8$ km that we obtain from the fits is in fact the radius of the innermost stable orbit, the required spin parameter for a 7 $M_{\odot}$ black hole is $a_* = 0.89$.

Recently, Cui, Zhang, & Chen (1998) proposed that certain QPO features observed in several BHCs are produced by the precession of the accretion disk due to the relativistic dragging of the inertial frame around a spinning black hole. Using the 300 Hz QPO in GRO J1655−40 (Remillard et al. 1997) and the 67 Hz QPO in GRS 1915+105 (Morgan et al. 1997), they concluded that both Galactic superluminal sources contain a very rapidly rotating black hole ($a_* \sim 0.95$). Similarly, they interpreted the 6.7 Hz peak in GS 1124−68 (Belloni et al. 1997b) and the 8 Hz QPO in Cyg X-1 (Cui et al. 1997) as the same phenomenon, and they concluded that the black holes in these two sources are spinning less rapidly ($a_* \sim 0.35$, $a_* \sim 0.48$, respectively). Based on these results, Cui et al. (1998) proposed that the difference between BHCs that are also superluminal jet sources and otherwise "normal" BHCs is the spin of the black hole.

Both in GS 1124−68 and Cyg X-1, the QPOs used by Cui et al. to reach this conclusion were observed during a source transition through the intermediate state, identical to the one in GRO J1655−40 that we describe here. Remarkably, on August 14 and 18 the PDSs show a QPO feature moving from ∼6.5 to ∼0.8 Hz, which is very similar to those observed in GS 1124−68 and Cyg X-1. In all three sources the QPO is more prominent at higher energies, and both in GRO J1655−40 and in Cyg X-1 the frequency of the QPO is correlated to the break frequency of the band-limited noise component.

However, if we, as Cui et al. (1998) did in the case of GS 1124−68 and Cyg X-1, interpret this intermediate-state QPO in GRO J1655−40 as the precession frequency of the disk, we would derive a spin of the black hole of 0.35 on August 14, and ~ -0.1 to 0.1 on August 18 (see Cui et al. 1998, Fig. 2), in strong contradiction with the value of 0.89 from the spectral fits. This argues against the interpretation of the intermediate-state QPO as the precession frequency of the disk. Of course, these results cannot be used to rule out the possibility that the 300 and 67 Hz features in GRO J1655−40 and GRS 1915+105 are related to the frame dragging effect, but if they are, then our results provide a strong objection to a similar interpretation of the 6.7 and 8 Hz QPOs in GS 1124−68 and Cyg X-1. Either way, we must conclude that the hypothesis that the angular momentum of the black holes in superluminal sources is much higher than that of other BHCs is no longer supported by the observed differences in QPO properties between GRO J1655−40, on the one hand, and Cyg X-1 and GS 1124−68, on the other.

Finally, we can compare our results for GRO J1655−40 to those obtained for the other Galactic superluminal source, GRS 1915+105. By means of time-resolved spectral analysis, Belloni et al. (1997a) were able to explain all spectral changes observed in GRS 1915+105 as the effect of thermal-viscous instabilities in the radiation-pressure–dominated region of an accretion disk. Based on the fit results to different parts of the highly variable X-ray light curve, they infer values of $\dot{M}$ of $\sim(1.7–10) \times 10^{-8}\ M_\odot\ \mathrm{yr}^{-1}$ during the quiescent phase (the range being determined by the uncertainty in the spin of the central black hole), and a factor of 2 higher during the so-called burst phase. The accretion rates estimated here for GRO J1655−40 are about an order of magnitude lower than those of GRS 1915+105 during its quiescent phase. It is possible that the complicated variability in the X-ray light curve of GRS 1915+105, which is not observed in GRO J1655−40, is entirely a result of the higher accretion rate in that source (although a higher mass, and therefore Eddington luminosity of GRS 1915+105, may compensate this). A natural consequence of this hypothesis is that, at higher accretion rates GRO J1655−40 (and other BHCs) should display a behavior similar to the one observed in GRS 1915+105, while on the other hand, at lower accretion rates GRS 1915+105 should undergo a source transition similar to the one described here for GRO J1655−40.

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