A TRANSITION TO THE SOFT STATE IN GRS 1758−258

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ABSTRACT

Near the end of 2001 February, the black hole candidate (BHC) GRS 1758−258 made an abrupt transition from a standard hard (low) state to a soft state. Unlike Cygnus X-1 and other BHCs, whose luminosity increases during this transition, GRS 1758−258 was dimmer after the transition. We present observations with the Proportional Counter Array on the *Rossi X-Ray Timing Explorer* and interpret the phenomenon in the context of a "dynamical" soft-state model. Using this model, we predicted that mass transfer from the companion had ceased and that the luminosity should decay on a timescale of a few weeks. The most recent data support this prediction, being consistent with a decay time of 28 days. The current state is consistent with the "off" state of GRS 1758−258 reported by SIGMA/*Granat* in 1991–1992.

Subject headings: accretion, accretion disks — black hole physics — stars: individual (GRS 1758−258) —
X-rays: stars

1. INTRODUCTION

GRS 1758−258 is one of only three black hole candidates (BHCs) usually near its maximum luminosity and usually in the hard state (the other two are Cygnus X-1 and 1E 1740.7−2942). It displays shot-noise flickering and quasi-periodic oscillations with characteristic timescales on the order of 1 s (Smith et al. 1997; Lin et al. 2000). It shows a core source and lobes in the radio (Rodríguez, Mirabel, & Martí 1992), which caused it to be one of the first sources referred to as a "microquasar."

The spectrum of GRS 1758−258 is generally a power law (with an exponential cutoff beginning around 100 keV), occasionally with a weak thermal component (Mereghetti, Beloni, & Goldwurm 1994; Heindl & Smith 1998). Weekly observations with the Proportional Counter Array (PCA; Jahoda et al. 1996) on the *Rossi X-Ray Timing Explorer* (*RXTE*) show that the power-law index can vary from about 1.5 to 2.5, that the hard X-ray luminosity is always dominated by the power law, and that the variability before 2001 (Fig. 1) was not extreme (Main et al. 1999; Smith, Heindl, & Swank 2001a). Earlier observations by SIGMA/*Granat* at 40–150 keV showed the source below the detection level in the fall of 1991 and spring of 1992 (Gilfanov et al. 1993) and therefore more than an order of magnitude fainter than its typical *Granat* and *RXTE* luminosity. The Burst and Transient Source Experiment (BATSE) on the *Compton Gamma Ray Observatory* also saw the 20–100 keV flux from GRS 1758−258 vary dramatically (Zhang, Harmon, & Liang 1997c).

GRS 1758−258's spectral variations are not simultaneous with the variations in its luminosity, a newly discovered characteristic that it shares with 1E 1740.7−2942 (Main et al. 1999; Smith et al. 2001a). In Cyg X-1, the usual prototype of a BHC system, there is a clearly defined progression from the hard state to the soft state: the 2–10 keV flux increases dramatically as the spectrum softens, the total X-ray luminosity increasing only slightly (Zhang et al. 1997b; Gierliński et al. 1999). The softening takes two forms: the index of the power law softens while, at the same time, the thermal component brightens and

goes to a higher temperature. In the transition back to the hard state, the spectrum and luminosity also vary simultaneously.

GRS 1758−258 and 1E 1740.7−2942, in contrast, tend to be softest not when the 2–10 keV flux is highest but rather when the derivative of that count rate is most negative (Smith et al. 2001a). We interpreted this behavior in terms of a model by Chakrabarti & Titarchuk (1995) in which BHC accretion operates in two decoupled flows: (1) a classical thin disk that produces thermal emission and (2) a nearly spherical, sub-Keplerian flow (hereafter "halo") that scatters the thermal photons into the cutoff power law. If the mass transfer from the companion suddenly dropped, altering both flows at large radii, the change would propagate at the free-fall timescale in the halo, but at a much slower viscous timescale in the thin disk. Therefore, there would temporarily be an imbalance: the same number of soft disk photons but fewer hot halo electrons to scatter them. Fewer scatters per photon softens the power law, and in addition, the thinner halo would be more easily cooled by the disk photons. In Smith et al. (2001a), we dubbed this a "dynamical" soft state and hypothesized that it was responsible for almost all the softening events observed in GRS 1758−258 and 1E 1740.7−2942, except for a brief period in the fall of 2000 when GRS 1758−258 was at its brightest and seemed on the verge of entering a true ("static") soft state in which the halo self-cools and collapses. In this Letter, we report on the recent transition of GRS 1758−258 to the soft state and interpret the data in terms of the dynamical soft-state model.

2. OBSERVATIONS

PCA snapshots of 1500 s were taken monthly of GRS 1758−258 in 1996, weekly through 2000, and are being taken twice weekly from 2001 March. There are no pointings for a period from November to January each year because of a Sun-angle constraint on pointing. Figure 1 shows the count rate as a function of time in two energy bands: 2.5–4.0 and 10.0–25.0 keV. Instrumental background and background due to Galactic plane diffuse emission (Smith et al. 1997; Main et al. 1999) have been subtracted. The source is kept off-axis to prevent contamination from GX 5−1 nearby. All results below use data from layer 1 of the PCA only. The data were analyzed with version 5.0.4 of HEAsoft.

There was a precipitous drop above 10 keV in late February of 2001 (Fig. 1), but not in the soft band (Smith et al. 2001b,

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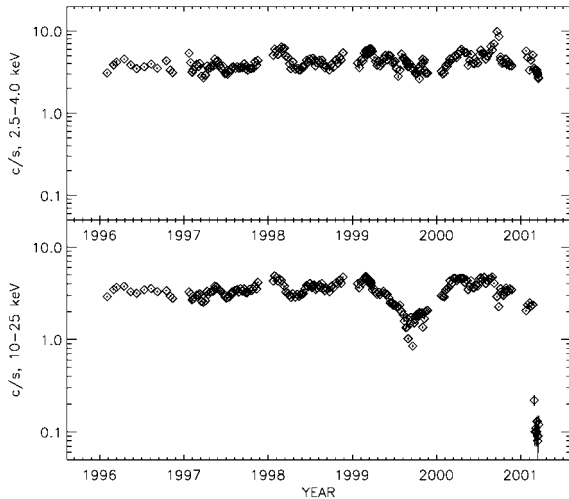[3] NASA Goddard Space Flight Center, Code 666, Greenbelt, MD 20771.

FIG. 1.—PCA count rate from GRS 1758−258 vs. time in two energy bands. These are raw count rates per PCU in layer 1. A PCU (Proportional Counter Unit) is one of the PCA's five detectors.

2001c). On March 12–13, 31 ks of public observations were made with *RXTE* in three separate intervals. Since the new soft state would have been undetectable to SIGMA, it is quite possible that this was the state that instrument observed in 1991–1992.

3. RESULTS

Figure 2 shows the PCA spectrum of the combined March 12–13 data, including the residuals from a fit to a power law plus a blackbody. Because the PCA fits begin at 3 keV, the fitted hydrogen absorption column and blackbody intensity are strongly correlated, and both cannot be determined well. We therefore fixed the column at the *ASCA* value (Mereghetti et al. 1997): 1.5×10^{22} atoms cm^{-2}. The fitted blackbody temperature was 0.395 ± 0.006 keV, and the power-law photon index was 2.89 ± 0.12. Using a multicolor disk blackbody, the maximum temperature was 0.464 ± 0.007 keV, and the power-law index was 2.75 ± 0.12. The blackbody luminosity (3.0×10^{-9} ergs cm^{-2} s^{-1}, or 2.6×10^{37} ergs s^{-1} at 8.5 kpc) is the highest seen with *RXTE*, although only about 35% higher than in some spectra from near the peak in the top panel of Figure 1 in late 2000.

As is apparent from the residuals in Figure 2, the addition of an iron K-shell line improves the fit. Fixing the energy at 6.7 keV and the width at 0.1 keV (narrower than the PCA resolution), the derived equivalent width is 300 eV for both the blackbody and disk blackbody models. The interpretation of a weak, instrumentally broad line near the crossover point of two continuum components is problematic, and we do not claim this as a certain detection. No significant improvement in χ^2 resulted from letting the energy or width of the line vary.

Figure 3 shows the fits to the monitoring observations in early 2001, before and after the state transition. The first observation of 2001 (January 23, labeled "A" in Fig. 3) displays both a bright power law and a significant blackbody peak (this is also occasionally seen at other periods from 1996 to 2000). The soft excess from 1.0 to 2.4 keV measured by Mereghetti et al. (1994) with *ROSAT* in 1994 was 2.8×10^{-10} ergs cm^{-2} s^{-1}, about half the value for this spectrum (5.7×10^{-10} ergs cm^{-2} s^{-1} from 1.0 to 2.4 keV, or 7.0×10^{-10} ergs cm^{-2} s^{-1} bolometric). The remain-
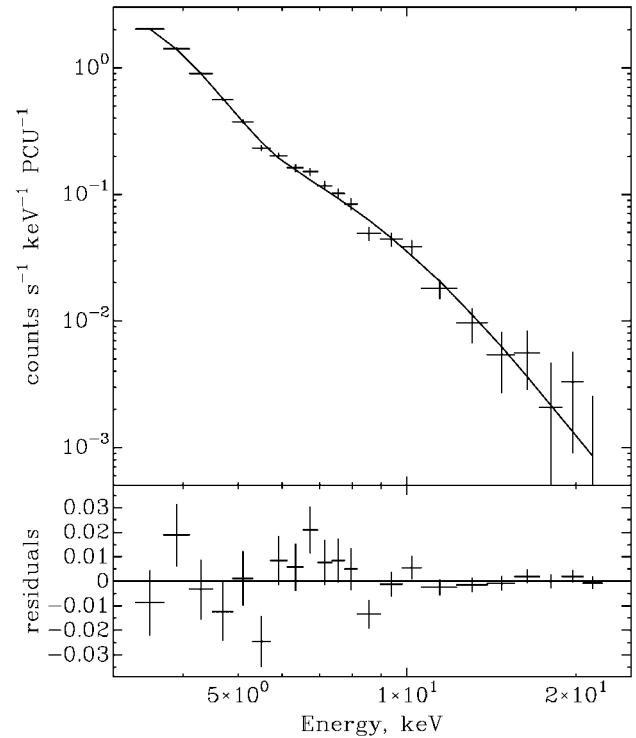

FIG. 2.—*Top panel*: Count spectrum and power-law plus blackbody fit for the deep PCA pointing in the soft state of GRS 1758−258. For display, the data from all four PCUs and all three parts of the deep pointing are summed. The fits used to derive the parameters mentioned in the text were simultaneous fits to independent data sets representing each PCU in each part of the deep pointing. *Bottom panel*: Residuals between the data and the fit.
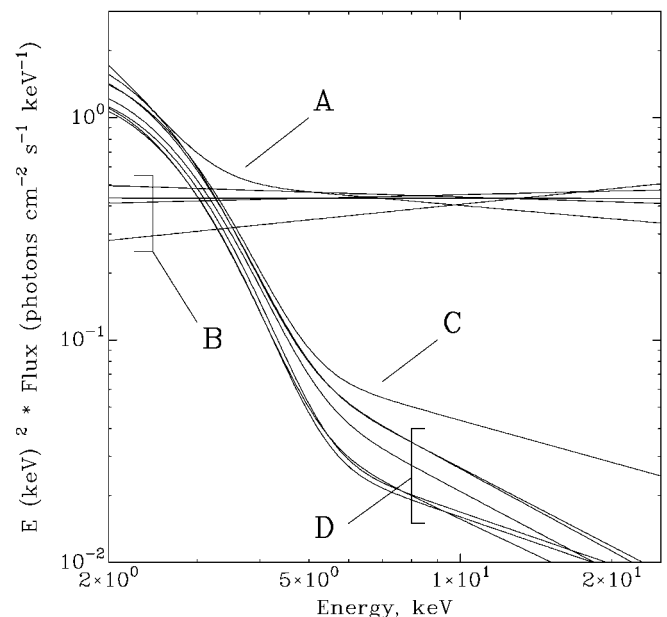

FIG. 3.—Fitted spectral models from January 23 to March 18: curve A is for January 23, curve B is for January 29–February 21, curve C is for February 27, and curve D is for March 2–18. The effect of interstellar absorption has been removed.

ing spectra before the transition have no detectable blackbody and a harder power-law index. The first spectrum after the transition (labeled "C") has somewhat more of a residual power-law tail than the spectra after it.

Figure 4a shows a combined light curve around the time of the transition, using data from two sources: the monitoring campaign discussed above and a second *RXTE* campaign of twice-weekly scans of the whole Galactic bulge region (Markwardt et al. 1999; C. B. Markwardt et al. 2001, in preparation). For each scan, the data are fitted to a model of point sources and diffuse emission. One scan point on February 20 implies that the source may have dropped to a low level in less than 3.9 days and then rebounded completely less than 11.3 hr later. Generally speaking, the pointed observations and bulge-scan intensities agree to within ∼2 σ. However, the proximity of GRS 1758−258 to the bright source GX 5−1 may potentially introduce unmodeled systematic errors into the scan data.

Figure 4b shows the evolution of the rms variability beyond Poisson noise. As is typical for BHC soft states (e.g., Maejima et al. 1984), the variability drops dramatically. The last data point represents all the deep-pointing data from March 12 to 13. At this time, the rms variability (0.004–16 Hz, 2–10 keV) was consistent with zero, with a 3 σ upper limit of 2.5%.

4. DISCUSSION

There are similarities and differences between this hard-to-soft transition and transitions in other BHCs. One of the best-monitored transitions was in Cyg X-1 in 1996. The 1.3–200 keV luminosity as measured by the *RXTE* All-Sky Monitor and BATSE, corrected for interstellar absorption, jumped upward by about 35% (Zhang et al. 1997b). To compare, we extrapolated our spectral fits to this energy range and removed the interstellar absorption using the fixed column density discussed above. GRS 1758−258 and other BHCs have an exponential cutoff in the hard state beyond the PCA range, and we used cutoff parameters from a deep *RXTE* pointing to GRS 1758−258 in 1996 (Heindl & Smith 1998). We find that the extrapolated 1.3–200 keV luminosity of GRS 1758−258 dropped in the hard-to-soft transition by about the same amount that it rose in Cyg X-1 in 1996.

That soft state in Cyg X-1, however, was not typical of BHC soft states in general. The power-law flux at 25 keV dropped by only a factor of 3 from the hard state (Zhang et al. 1997a) compared with the factor of 50 apparent in Figure 3, and there was still 20% rms of fast variability (Cui et al. 1997). This led Belloni et al. (1996) to conclude that this "soft" state should have been called an "intermediate" state. If the hard/intermediate/soft progression is a monotonic increase in accretion rate as generally thought, one would expect that the more "complete" transition in GRS 1758−258 would result in an even larger increase in luminosity, not a decrease.

GX 339−4 entered the soft state in 1990 and 1998 with similar spectral and timing characteristics to the new soft state in GRS 1758−258. Between April and August of 1990, the power-law tail in GX 339−4 dropped by at least an order of magnitude at 10 keV, and the rms variability in the soft state was only 6.1% ± 2.7% (Grebenev et al. 1991). For the 1998 transition, Belloni et al. (1999) compared the 2.5–20 keV unabsorbed flux in the soft state with data taken in the hard state several months previously. They found that the total flux in this band increased by about a factor of 2. We can evaluate our PCA data in this band without extrapolation. Again, we find that contrary to the behavior of the other BHC, GRS
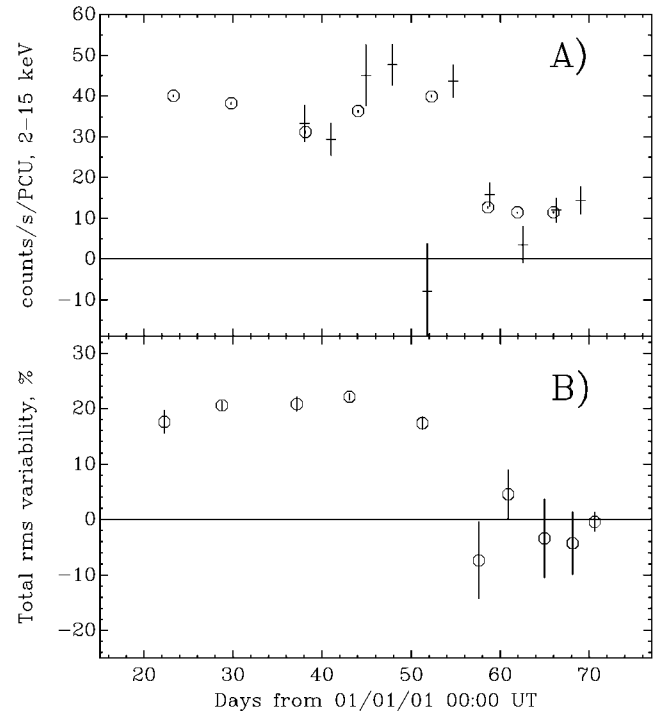

FIG. 4.—Evolution of count rate and rms variability in GRS 1758−258 around the state transition. (*a*) PCA count rate from 2 to 15 keV, showing both the monitoring data of Fig. 1 (*circles*; the error bars are almost too small to see) and the data from the Galactic bulge scans (*crosses*; see text). Note the brief drop to low flux around day 51 (February 20). (*b*) Total rms variability from 0.004 to 16 Hz and from 2 to 10 keV. Poisson noise has been subtracted.

1758−258 saw a decrease in absorption-corrected flux in the energy band chosen for comparison, in this case a drop of a factor of 3.3 from 2.5 to 20 keV between February 21 and March 2.

BATSE was the first to observe a soft state in 1E 1740.7−2942, with a power-law index of −2.6 from 20 to 100 keV (Zhang et al. 1997c). The soft spectrum crossed the usual harder spectrum at 20 keV, so again there would have been an increase rather than a drop in the power-law component over the 3–25 keV band.

While the transitions in Cyg X-1, GX 339−4, and other BHCs are probably caused by an increase in accretion, causing the self-cooling and partial collapse of the halo (the static soft state), we suggest that this transition in GRS 1758−258 is caused instead by the sudden shutoff of all, or nearly all, of the mass transfer from the compact object's companion. This is the extreme instance of the dynamical soft state described in Smith et al. (2001a). Given the hypothesis (Chakrabarti & Titarchuk 1995) that the disk and halo flows are independently fed directly from the companion, the halo would then vanish immediately, leaving the disk to decay away on a viscous timescale on the order of a month or more (Main et al. 1999; Smith et al. 2001a). We would not expect Cyg X-1 to show a dynamical soft state because, as a wind accretor, its disk is expected to be small and therefore to have a short viscous time (Smith et al. 2001a).

It is possible that beneath the halo, the disk emission was more or less constant throughout early 2001, and when it was not seen, the halo was optically thick. In the first spectrum of the year (curve A in Fig. 3), with a blackbody luminosity about a factor of 4 below the naked disk, the optical depth of the halo would

then have been near unity. The changes in the slope of the power law support this interpretation: the slope is hardest when the halo is assumed to be thickest, and repeated scatterings should produce a harder power law (Shapiro, Lightman, & Eardley 1976). If the apparent drop on February 20 (Fig. 4a) is genuine, then the time for the halo to reestablish itself would be less than 11.3 hr, which is still longer than the free-fall time from the outer disk.

Viewing the disk and halo flows as independent and assuming that the disk flow did not change as the halo disappeared, the loss of fast variability in the transition implies that the flickering commonly observed in the hard state of BHCs is either intrinsic to the halo flow alone or else due to an interaction at the boundary between the dense, radially slow-moving disk and the thin, radially fast-moving halo.

When the transition to the soft state occurred, we predicted (Smith et al. 2001b), based on the dynamical picture and the disk timescales we previously derived (Main et al. 1999; Smith et al. 2001a), that mass transfer from the companion had stopped and that the soft-state emission would decay away with a timescale of a few weeks. Figure 5 shows the flux (uncorrected for absorption) from 3 to 25 keV as a function of time starting with the first soft-state spectrum (February 27) and ending with the most recent data available (April 15). The shape is neither exponential nor linear, but somewhere in between. The best-fit exponential gives a 27.9 ± 1.7 day time constant. The latest fluxes approach the limit of the systematic uncertainty in the Galactic diffuse emission.

If there is still a small mass transfer from the companion, the spectrum may eventually make a transition to the pure, very faint hard power law seen in GX 339−4 in its lowest luminosity ("off") state (Maejima et al. 1984; Ilovaisky et al. 1986; Méndez & van der Klis 1997; Asai et al. 1998; Kong et al. 2000).
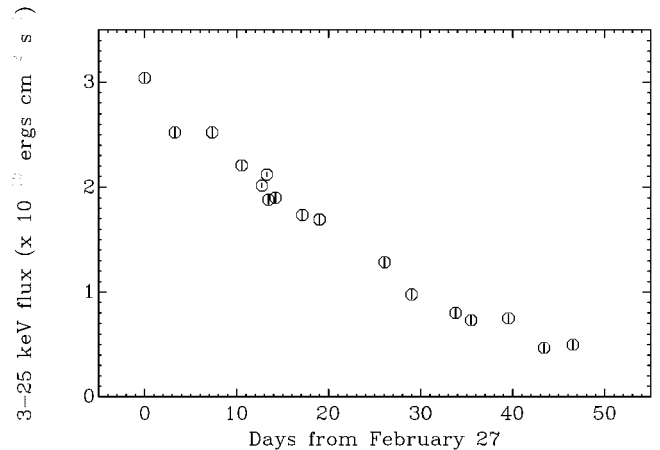

FIG. 5.—Energy flux in GRS 1758−258, 3–25 keV, as a function of time since the state transition on February 27, uncorrected for interstellar absorption. Note that the scatter of the data is much greater than the error bars, which are shown, so that the quality of a fit to any smooth function is poor (reduced $\chi^2 \sim 10$).

Observations of GX 339−4 were never taken immediately following the drop from higher fluxes, and it may show a dynamical soft state at those times. Eventually, our understanding of the state change in GRS 1758−258 may apply to the state changes in the soft X-ray transients (the outbursts of the more numerous BHCs without persistent emission), which can show hysteresis with a hard-to-soft transition near peak flux followed by a much later soft-to-hard transition at much lower flux (Miyamoto et al. 1995).

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