ABSTRACT

We report results of a comprehensive study of the soft $\gamma$-ray (30 keV to 1.7 MeV) emission of GRO J0422+32 during its first known outburst in 1992. These results were derived from the BATSE earth occultation database with the JPL data analysis package, EBOP (Enhanced BATSE Occultation Package). Results presented here focus primarily on the long-term temporal and spectral variability of the source emission associated with the outburst, which complement those reported earlier by BATSE, OSSE, COMPTEL, and SIGMA. The light curves with 1 day resolution in six broad energy bands (e.g., 35–100, 100–200, 200–300, 300–400, 400–700, and 700–1000 keV) show that the high-energy flux (>200 keV) led the low-energy flux (<200 keV) by ~5 days in reaching the primary peak, but lagged the latter by ~7 days in starting the declining phase. We confirm the “secondary maximum” of the low-energy (<200 keV) flux at ~TJD 8970–8981, ~120 days after the first maximum, reported earlier by the BATSE team. Our data show that the secondary maximum was also prominent in the 200–300 keV band, but became less pronounced at higher energies. During this 200 day period, the spectrum evolved from a power law with photon index of 1.75 on TJD 8839, to a shape that can be described by a Comptonized model or an exponential power law below 300 keV, with a variable power-law tail above 300 keV. The spectrum remained roughly in this two-component shape until around November 9 (TJD 8935), when the 35–429 keV luminosity dropped to below ~20% of its peak value observed on TJD 8848. It then returned to the initial power-law shape with an index of ~2 and stayed in this shape until the end of the period. The correlation of the two spectral shapes (e.g., Compton/power law tail vs. power law) with the high and low luminosities of the soft $\gamma$-ray emission is strongly reminiscent of that seen in Cyg X-1, suggesting that similar processes are at work in both systems. We also observed four separate episodes of high-energy (400–1000 keV) emission during the first 84 days of the event. We interpret these results in terms of the advection-dominated accretion flow (ADAF) model with possibly a “jetlike” region that persistently produced the nonthermal power-law $\gamma$-rays observed throughout the event.

Subject headings: black hole physics — gamma rays: observations

1. INTRODUCTION

The $\gamma$-ray source GRO J0422+32 was first discovered by the Burst and Transient Source Experiments (BATSE; Fishman et al. 1989) on board the Compton Gamma Ray Observatory (CGRO) on 1992 August 5 (Paciesas et al. 1992). Early BATSE results (Harmon et al. 1992, 1994) reported by the Marshall Space Flight Center (MSFC) PI team showed that the source underwent a major outburst when the hard X-ray (40–230 keV) flux reached a level of ~3 Crab in about 3 days. It remained at this level for at approximately 3 days and then decreased exponentially with a time constant of 43.6 days (Vikhlinin et al. 1995). A secondary maximum was then observed approximately 120 days after the first maximum, in 1992 December (Harmon et al. 1994), again followed by an exponential decay with timescale similar to that of the first maximum. The entire outburst lasted for about 200 days before returning to the preburst quiescent level.

Observational data in UV/optical/IR/radio (Castro-Tirado et al. 1992, 1993; Wagner et al. 1992; van Paradijs & McClintock 1995; Shadrake et al. 1992a, 1992b, 1994; Chevalier & Ilovaisky 1995, 1996; Bonnet-Bidaud & Mouchet 1995; Callanan et al. 1996; Casares et al. 1995; Garcia et al. 1996) and in X-ray and $\gamma$-ray (Sunyaev et al. 1993; Pietsch et al. 1993; Harmon et al. 1994; Roques et al. 1994; Vikhlinin et al. 1995; van Dijk et al. 1995; Grove et al. 1998; Ling et al. 2000; Iyudin & Haberl 2001) of this event and subsequent outbursts have also been reported in the literature. An optical counterpart of GRO J0422+32 was observed by Castro-Tirado et al. (1992, 1993) and Wagner et al. (1992) showing a visual magnitude of ~1.75 on TJD 8839, to a shape that can be described by a Comptonized model or an exponential power law below 300 keV, with a variable power-law tail above 300 keV. The spectrum remained roughly in this two-component shape until around November 9 (TJD 8935), when the 35–429 keV luminosity dropped to below ~20% of its peak value observed on TJD 8848. It then returned to the initial power-law shape with an index of ~2 and stayed in this shape until the end of the period. The correlation of the two spectral shapes (e.g., Compton/power law tail vs. power law) with the high and low luminosities of the soft $\gamma$-ray emission is strongly reminiscent of that seen in Cyg X-1, suggesting that similar processes are at work in both systems. We also observed four separate episodes of high-energy (400–1000 keV) emission during the first 84 days of the event. We interpret these results in terms of the advection-dominated accretion flow (ADAF) model with possibly a “jetlike” region that persistently produced the nonthermal power-law $\gamma$-rays observed throughout the event.

There was also evidence showing the source is a binary system. Filippenko, Matheson, & Ho (1995) observed a 5.08 ± 0.01 hr orbital period, and estimated a mass function of $f(M) = 1.21 ± 0.06 M_\odot$. The mass function is consistent with $f(M) = 0.40 ± 0.14 M_\odot$ reported by Orosz & Bailyn (1995), and $0.85 ± 0.30 M_\odot$ reported by Casares et al. (1995). Using the orbital inclination of $i = 45^\circ$ determined by Callanan et al. (1996), the mass of the compact object is estimated to be $3.4 M_\odot$. However, based on the orbital inclination of $10^\circ$–$31^\circ$ estimated independently from infrared and optical photometry, a lower limit of $9 M_\odot$ for the compact object is implied, which strongly suggested the existence of a black hole in the system. The distance of the source was estimated by Shadrake et al. (1994) to be $2.4 ± 0.4$ kpc.
The black hole nature of GRO J0422+32 was also supported by X and γ-ray observations. First, the contemporaneous X-ray and soft γ-ray spectra measured by the TTM and HXTE instruments (Sunyaev et al. 1993; Maisack et al. 1994) in the 2–300 keV range on board the Mir Kvant spacecraft, and SIGMA (Roques et al. 1994) in the 35–600 keV range on board the Granat spacecraft, and by BATSE (Harmon et al. 1994; Ling et al. 2000), OSSE (Grove et al. 1998), and COMPTEL (van Dijk et al. 1995) on CGRO in the 50 keV to 2 MeV range can generally be characterized by either an exponentially truncated power-law with a photon power-law index of 1.49 ± 0.01, break energy $E_b$ of $60 ± 3$ keV, and $c$-folding energy $E_c$ of $132 ± 2$ keV, or in terms of a Comptonized disk model (Sunyaev & Titarchuk 1980) with a temperature of $kT$ ~ 58 keV and an optical depth of ~2.

It is interesting to note that the SIGMA spectrum (Roques et al. 1994) shows excess flux from 400 to 600 keV above the best-fit Comptonized model, and that high-energy flux was also observed from 1 to 2 MeV by COMPTEL (van Dijk et al. 1995). The composite spectral shape, Comptonized below and power-law above 400 keV, respectively (see Ling et al. 2000; and Fig. 3 below, panels 36–39) strongly resembles the standard-state ($\gamma_2$, or X-ray low/hard-state) spectrum of Cyg X-1 (Ling et al. 1987, 1997; McConnell et al. 2000, 2002), the best-known black hole candidate in our Galaxy.

Second, the timing analysis of the hard X-ray data of BATSE (20–300 keV; Kouveliotou et al. 1993; Kouveliotou 1994; van der Hooft et al. 1999), and SIGMA (45–150 keV; Vikhlinin et al. 1995) showed evidence for low-frequency quasi-periodic oscillation (QPOs) centered at 0.03 and 0.2 Hz for the former and 0.3 Hz for the latter. These results are consistent with the frequencies observed by OSSE (Grove et al. 1994). Because of similar low-frequency QPOs observed in other black holes (Sunyaev et al. 1991; Van der Klis 1994; Roques et al. 1994), it has been suggested (Roques et al. 1994) that the GRO J0422+32 could be a black hole also.

While previous soft γ-ray results (30 keV to 2 MeV; Harmon et al. 1992, 1993, 1994; Sunyaev et al. 1993; Maisack et al. 1994; Roques et al. 1994; van Dijk et al. 1995; Grov et al. 1998; Ling et al. 2000) have advanced our understanding of the system, information concerning the long-term behavior of the source during the outburst is far from complete. The earlier BATSE published light curve (Paciesas et al. 1992; Harmon et al. 1992, 1993) primarily focused on the energy region below 200 keV. The spectra measured by COMPTEL, OSSE, and SIGMA focused on only isolated periods of the 200 day event, in part because of the relatively spotty coverage of pointed observations made by most of these experiments. Questions that need to be addressed include: (1) How does the source spectrum evolve over the course of the event? and (2) What is the long-term behavior of the high-energy flux above 200 keV compared to that below 200 keV (Harmon et al. 1994; Grove et al. 1998)?

Answers to these questions will shed further light on the mechanism driving the outburst, and ultimately the physical makeup of the system itself.

This paper addresses these important questions. Our results were obtained using BATSE Earth occultation data provided by the BATSE PI team at MSFC (Fishman et al. 1989), processed and analyzed using the JPL Enhanced BATSE Occultation Package (EBOP; Ling et al. 1996, 2000). A brief description of the EBOP database and technique are given in § 2. Results produced by EBOP are presented in § 3.
Fig. 1.—Flux histories, with 1 day resolution in six separate energy bands. The high-energy (panels 3–6) flux rose more sharply and reached the first of the four episodic peaks (shown by four vertical dashed lines a, d, e, and f) on TJD 8843 (line a) five days before the first low-energy subpeak (line b) on TJD 8848. The decrease of the low-energy flux between the first and the second subpeaks on TJD 8855 (line c) is only ~5%. However, the decrease of the high-energy fluxes (panels 3–6) between its first and second subpeak on TJD 8862 (line d) is significantly more pronounced. The high-energy fluxes also lagged the low-energy fluxes in starting the decline phase by ~7 days (see lines c and d). A broad “secondary maximum” for the low-energy fluxes ~120 days later at ~TJD 8970–8981, which was observed and reported by the BATSE team earlier (Harmon et al. 1993), was also prominently observed in the 200–300 keV bin, but became less pronounced at higher energies. Note that there is also evidence for a “dip” in intensity at around TJD 8977 in the midst of the secondary maximum which is shown in all six energy bands.
We observed also for the first time energy-dependent flux variability above 200 keV (see Fig. 1, panels 3–6). These data show temporal features significantly different than those observed below 200 keV. First, the high-energy flux rose more promptly after the onset and reached the first maximum of the 35–200 keV flux (line b). It then declined in the next nine days before rising to a second maximum on August 28 (TJD 8862; line d), 7 days after the second maximum (line c) and during the declining phase of the hard X-ray (35–200 keV) flux. The flux ratio of the second to first maximum increased with energies, ranging from ~1 for 200–300 keV, 1.3 for 300–400 keV, ~2 for 400–700 keV, to ~3.3 for 700–1000 keV. The local minimum around TJD 8850 became more pronounced with increasing energy. The flux ratio of this minimum to the second maximum decreased from ~0.9 for 200–300 keV, ~0.4 for 300–400 keV, ~0.2 for 400–700 keV, to ~0 for 700–1000 keV. Variable high-energy fluxes were also consistently observed in the three high-energy channels (300–400, 400–700, and 700–1000 keV) at least two other periods centered at ~TJD 8889 (third maximum, line e) and TJD 8919 (fourth maximum, line f), interspersed with periods of low γ-ray flux at ~TJD 8875 and 8900. Spectra measured during these highly variable γ-ray flux periods are presented in detail in the next section. The broad secondary maximum observed in 35–200 keV was also prominently observed in 200–300 keV at ~TJD 8970–8981, ~120 days after the primary peak, but became less pronounced at higher energies. There is also a dip in intensity at around TJDs 8973–8977 in the midst of the secondary maximum, similar to that seen in the primary peak. Such a dip is consistently seen in all six energy bands. Its significance is estimated to be ~5 σ at 200–300 keV. Iyudin & Haberl (2001) showed that the γ-ray emission, based on 25 observations by COMPTEL obtained between 1992 August and 1997 August (~1800 days) and three viewing periods before the 1992 outburst, is primarily confined between 1.5 and 2 MeV, and was more prominent during phases from 0.0 to 0.5 of the 120 day period, where zero phase corresponds to TJD 8840.5. Our BATSE results show that the high-energy fluxes were confined to phases from 0.0 to 0.7 of the same periodicity. The averaged flux of the 700–1000 keV emission integrated over TJD 8841–8923 (~phase 0–0.7) is (1.6 ± 0.3) × 10^{-6} photons cm^{-2} s^{-1} keV^{-1}, compared to (−4.9 ± 5.1) × 10^{-1} photons cm^{-2} s^{-1} keV^{-1} integrated over TJD 8925–8960 (~phase 0.7–1.0). Similarly, for the 400–700 keV emission, the averaged fluxes for the same two periods are (10.0 ± 0.6) × 10^{-6} and (1.3 ± 0.8) × 10^{-6} photons cm^{-2} s^{-1} keV^{-1}, respectively.

3.2. Spectra

The complex energy-dependent flux histories shown in Figure 1 imply complex spectral changes over the course of the 200 day event. We selected a sample of 36 single-day spectra spanning the period from TJD 8839 to 9933 to show such changes. Pertinent information related to each of these spectra is given in Figure 2 and Table 1. For each day, the source was observed by two to four of the eight BATSE LADs with good sensitivity. These “source-viewing” LADs, which are identified in Table 1 and Figure 2, were selected using the criteria discussed by Ling et al. (1996, 2000). Each LAD spectrum has 14 energy bins. The solid line shows the best-fit model (either Compton model or power law) to the n data points, where n = number of LADs ×14 energy channels, using the standard analysis fitting program XSPEC (Arnaud 1996). The best-fit model parameters, as well as reduced χ^2 (χ^2/ν, where ν is the number of degrees of freedom) of the fit are also displayed in each panel and listed in Table 1. In 12 of the 36 panels (e.g., panels in the middle column in each of the four pages) in Figure 2, spectra measured simultaneously by all source-viewing LADs on that day are shown and compared. Since each LAD spectrum was independently determined over a complex background that is totally different from that of the other seven LADs, these simultaneously measured spectra allow one to assess the quality and consistency of the results. Consistency of fluxes among all source-viewing LADs is also reflected by the goodness of the model fits to the data (Ling et al. 1996, 2000). Large reduced χ^2 could be caused by either inconsistency of LAD fluxes or inadequacy of the spectral model. Twenty-nine of the 36 spectra in Figure 2 have acceptable fits with either a power law or a Compton model. The relatively large reduced χ^2 shown in panels 13–21 (~TJDs 8855–8883, taken around the second maximum of the high-energy fluxes) are due primarily to a spectral tail above 300 keV. In general, the consistency among LADs in the 36 spectra in Figure 2 gives us good confidence in the analysis technique and results. Having developed data analysis systems for four separate missions (e.g., OSA-7, HEAO-1, HEAO-3, and CGRO) in the past three decades, and shared the frustration of many others of the disparate results produced by different experiments, some of which could be caused by systematic effects associated with the inadequacy of the data analysis techniques, we believe it is useful to show internal consistency achieved among the relevant detectors of a single instrument, such as BATSE. This was an important goal for EBOP. We hope the results presented here will encourage other investigators to show internal consistency, as a necessary quality control requirement in future γ-ray data analysis.

Key spectral results shown in Figures 2 and 3 and Table 1 are summarized below.

3.2.1. High-State Spectrum and Variability

1. During the rising phase of the event, the single-day spectrum shown in Figure 2a changed from a power law with photon index of 1.75 on TJD 8839 (Fig. 2a, panel 1) to, 2 days later, a shape better characterized by a single-temperature analytic Compton model (Sunyaev & Titarchuk 1980), with kT = 59 ± 5 keV and τ = 2.27 ± 0.19, on TJD 8841 (Fig. 2a, panel 2). The reduced χ^2 for a power-law fit to the TJD 8841 spectrum is 2.9, compared to 0.66 for the Compton model (see Table 1), clearly indicating the change in spectral shape. In fact, the 4 day averaged spectra measured by the two source-viewing LADs (1 and 5) during viewing period (VP) 35 (TJD 8841–8844; see Fig. 3a, panel 1) show excesses of the high-energy (>300 keV) flux over the best-fit Compton model (solid line, kT = 51.1 keV, τ = 2.93). The dashed line shows the best-fit power law (α = 3.4) to the flux in the five high-energy channels (313–1700 keV) measured by the two source-viewing LADs (1 and 5). Such high-energy flux was only hinted at in the corresponding single-day spectra (Fig. 2a, panels 2–5) because of statistical limitations of the data. The two-component (Compton+power law) spectrum is strongly reminiscent of the γ2 spectrum (or “low/hard” X-ray state) of Cyg X-1.
Fig. 2. — (a) Sample of nine single-day spectra, selected to show the evolutionary changes of the source spectrum during the first 12 days (TJD 8839–8850) of the 200 day event (see also Fig. 1). The spectrum evolved from the “low-intensity” power-law shape at the onset on TJD 8839 to a “high-intensity” Comptonized shape below 300 keV 2 days later on TJD 8841. A high-energy power-law component above 300 keV was also observed prominently in the VP 35 spectra shown in Fig. 3 during the first of the four “episodic” γ-ray emission periods. However, it was not clearly visible in the single-day spectra because of statistical limitation of the data. Note that in three panels of the middle column, spectra measured simultaneously by all source viewing LADs on that day are shown and compared. This is a self imposed consistent test to serve as “quality control” to ensure credibility of all EBOP results. (b) A second set of nine single-day spectra covering the period TJD 8851–8862 (identified as 10–18 in Fig. 1). During this period, the fluxes, specifically those below 200 keV, gradually rose from a local minimum at TJD 8850 to a peak at ~TJD 8862. While the spectrum averaged over the entire period (VP 37, see Fig. 3) remained in the same two-component shape, namely a Comptonized component below 300 keV followed by a variable power-law above 300 keV, that was visible even in the single-day spectra on TJD 8858, 8859 and 8862 (panels 16–18), respectively. (c) A third set of nine single-day spectra covering the period TJD 8863–8945 (identified as 19–27 in Fig. 1). During this period, the spectrum remained approximately in the same two-component shape (see also Fig. 3, panels 4–8), namely a Comptonized component below 300 keV and a variable power-law above 300 keV, until ~TJD 8935, when the 35–429 keV luminosity dropped to ~20% of the peak value (see also Table 1). The spectrum then returned to the initial power-law shape, that shown on TJD 8839 (Fig. 2a, panel 1) with index of ~2 (see panels 26 and 27). (d) A fourth set of nine single-day spectra covering the period TJD 8955–9033 (identified as 28–36 in Fig. 1). The spectrum stayed in the power-law shape throughout this period until the end of the event.
suggesting that similar physical processes were at work in both systems.

2. Figure 2, panels 6–25 and Figure 3, panels 2–8 show the single-day and multiple-day VP spectra, respectively, covering the period from TJD 8847 to 8925. This period includes: (1) the peak and decay phases of the event when the 35–429 keV luminosity was above 20% of the peak value (see Table 1), and (2) periods of the second (line d) and third (line f) high-energy peaks described in § 3.1. During this 78 day period, the spectrum underwent significant changes.

For the low-energy Comptonized component below 300 keV, as reflected by the best-fit parameters of the single-day spectrum shown in Table 1, the electron temperature ($kT$) varied from 40 to 60 keV and optical depth $\tau$ from 2.3 to 3.4. For the high-energy power-law component above 300 keV, seen more prominently in the VP spectra shown in Figure 3 (VPs 36.7, 37, 38, 39, 40, and 42), the best-fit photon index varied from $\sim 1$ in VP 42 to $\sim 3.8$ in VP 39. Details shown in Figure 3 also include:

A. Panel 2 shows the weighted averaged spectrum measured by four BATSE LADs (LADs 0, 2, 4, and 6) during...
VP 36.5 (TJD 8847–8853), the first local high-energy flux minimum described in § 3.1 item 2 (see also Fig. 1). The solid line is the best-fit Compton model with $kT = 42.2$ keV and $\tau = 3.52$ to the four source-viewing LAD spectra (LADs 0, 2, 4, and 6). The reduced $\chi^2$ for the fit is 1.38 for 53 degrees of freedom. Also shown in this panel is a comparison of the BATSE spectrum with those measured simultaneously by OSSE (retrieved from the OSSE archive in 1995; see also Ling et al. 2000) and COMPTEL (van Dijk et al. 1995). Below 429 keV, OSSE fluxes were generally lower than those of BATSE by ~5%–25%. Above 429 keV, upper limits measured by BATSE are consistent with the positive fluxes in the 518–678 keV bin measured by OSSE, and in the 750–1000 keV and 1000–2000 keV bins measured by COMPTEL (van Dijk et al. 1995). The high-energy fluxes measured by COMPTEL and OSSE in this period were lower than those measured by BATSE in VP 35 (e.g., by approximately a factor of 2 at 1 MeV). They provide, however, an important confirmation of the high-energy component of the two-component (Compton and power law) spectrum observed.
by BATSE in VP 35, and further suggest that such component is variable.

B. The high-energy component above 300 keV was also clearly visible in the four VP spectra that follow (Fig. 3, panels 3–6: VP 37, 38, 39, and 40), covering the period from TJD 8855 to 8902. The power-law indices for these four spectra vary from 2.3 to 3.8. The two larger indices of 3.44 and 3.83 for VP 37 and 39, respectively, correspond to the first (between lines a and d) and second (between lines d and e) peak for the high-energy flux shown in Figure 1, panels 5 and 6. None of these VP spectra can be adequately fitted with a single-component Compton model (solid line). The reduced \( \chi^2 \) for fitting these spectra varies from \( \sim 2.5 \) to \( \sim 8.4 \). The reasons for the poor fit are: (1) the presence of the high-energy flux above 300 keV in the spectrum and (2) short-term (single-day) spectral changes shown in Figure 2, due possibly to intrinsic changes in the system, preclude any possibility for a simple model (e.g., Compton model) to adequately fit the long-term VP spectrum. For three of the four VP spectra (VP 37, 38, and 40) in which high-energy fluxes are prominently visible, data measured by all source-viewing LADs are displayed to demonstrate their consis-

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**Fig. 2d**
More significantly, the weighted averaged VP 37 fluxes below 500 keV by few to 26% in VP 39, and 25%–47% in VP 39 and VP 39 spectra, respectively, extracted from the OSSE respectively. They correspond to the second and third sub-period. A relatively hard high-energy component was seen in the source viewing LADs (5 and 7). The difference of the fluxes corresponds to the third minimum (between lines e and f) shown in Figure 1, panels 5 and 6. C. The hardest high-energy component was seen in the VP 42 spectrum with a power-law index of $\sim 1$. Positive fluxes were measured in each of the five high-energy channels (313–429 keV), 429–595, 595–766, 766–1104, and 1104–1700 keV) at 13.8, 7.9, 6.2, 5.7, and 6.7 $\sigma$ significance, respectively. Furthermore, they were consistently seen by the two source-viewing LADs (5 and 7). The difference of the fluxes in each energy band measured by the two LADs was estimated to be 1.1, 0.8, 2.0, 0.4, and 0.2 $\sigma$ significance. Such hard MeV component reminds us of the "bump" seen in the $\gamma$-ray spectrum of Cyg X-1 (Ling et al. 1987).

3. Figure 4 shows a comparison of spectra measured simultaneously by BATSE and SIGMA (Roques et al. 1994) during the period from TJD 8850 to 8891. Above 300 keV, BATSE results were consistent with those of SIGMA. Below 300 keV, SIGMA results were generally lower by $\sim 20\%$ at 50 keV, $\sim 33\%$ at 100 keV, and $\sim 43\%$ at 200 keV. Since the source fluxes were highly variable during this
Fig. 3.—(a) Four consecutive viewing period (VP 35, 36.5, 37, and 38) spectra covering the initial phases of the outburst from TJD 8841 to 8865. A variable high-energy (>300 keV) power-law component superposed on the Compton component below 300 keV is clearly visible in panels 1, 3, and 4, which correspond to two of the high-flux periods (lines a and d) shown in Fig. 1. High-energy (>400 keV) fluxes measured by COMPTEL (van Dijk et al. 1995) and OSSE (from the OSSE archive; see Ling et al. 2000) during VP 36.5 are also included in panel 2 for comparison. Shown also in panel 3 for comparison are unpublished OSSE spectra for VPs 37. OSSE fluxes below 500 keV are generally lower than those of BATSE by ~25%–47% for VP 37. (b) A second group of consecutive viewing period (VP 39, 40, 41, and 42) spectra covering the period from TJD 8867 to 8923. During this period, two strong episodes of γ-ray emission were seen that peaked at ~TJD 8889 (see Fig. 1, line e) and TJD 8919 (see Fig. 1, line f), respectively. A strong variable high-energy (>300 keV) spectral component superposed to the Compton component below 300 keV, is clearly visible in the corresponding VP 40 and VP 42 spectra. OSSE unpublished spectrum for VP 39 (from OSSE archive; see Ling et al. 2000) is also included in panel 7 for comparison. These are generally lower than those of BATSE by a few percent to 26%. The strong 400–1700 keV fluxes that were consistently measured by the two source-viewing LADs (5 and 7) in VP 42 with a power-law index of ~1 are reminiscent of the MeV “spectral bump” seen in the γ1 spectrum of Cyg X-1 (Ling et al. 1987).
40 day period, part of the discrepancy below 300 keV may be due to differences in weighting the short-term daily fluxes in deriving the averaged spectrum.

3.2.2. Low-State Spectrum

When the 35–500 keV luminosity dropped below to 20% of the peak value observed on TJD 8848 (see Table 1) after TJD 8925, the source spectrum returned to a power law with indices of ~1.8–2 (see Fig. 2, panels 28–36), similar to that first seen at the start of the event on TJD 8839. Figure 5 shows a comparison of a 30 day averaged low-state spectrum observed on TJD 9010–9040 with the average high-state spectrum covering the six periods shown in Figure 3 from TJD 8841 to 8865 (VPs 35–38). The two spectra are clearly distinct. Above 300 keV, the low-state spectrum with
a power index of $\sim 2$ is harder than that of the high-state spectrum with index of $\sim 5.2$, and intersects the latter at $\sim 600$ keV. Similar spectral features and characteristic were also observed in Cyg X-1 between the X-ray low-state and high-state spectra (McConnell et al. 2002).

4. DISCUSSION

A comprehensive study of the long-term spectral and temporal properties of soft $\gamma$-ray emission of GRO J0422+32 shown in the 1992 outburst is the primary subject of this report. Highlights of our results are:

1. The light curves in the six energy bands (Fig. 1) show that the high-energy ($>200$ keV) flux led the low-energy flux ($<200$ keV) by $\sim 5$ days in reaching the initial peak, but lagged the latter by $\sim 7$ days before starting to decline.

2. We confirm the secondary maximum in the low-energy ($<200$ keV) flux at $\sim$TJD 8970–8981, $\sim 120$ days after the first maximum, as reported earlier by the BATSE team (Harmon et al. 1993). Such a secondary maximum was also prominently observed in the 200–300 keV band, but became less pronounced at higher energies (Fig. 1). We also observed a dip in intensity in all six energy bands at $\sim$TJDs 8973–8977 in the midst of the secondary maximum. The dip is similar to that seen during the primary peak $\sim 120$ days earlier.

3. During this 200 day period, the spectrum evolved from the low-intensity power-law shape with photon index of $1.75$ on TJD 8839, to a high-intensity shape of two components: a thermal Comptonization shape below 300 keV, with a power-law tail above 300 keV with variable index from $1$ to $4$ (Figs. 2 and 3).

4. The spectrum remained roughly in this two-component shape until around November 9 (TJD 8935), when the 35–429 keV luminosity dropped to $\sim 20\%$ of its peak value observed on TJD 8848. At that time, the spectrum returned to the initial power-law shape with an index of $\sim 2$ and stayed in this shape until the end of the event (Figs. 2 and 3; Table 1).

5. Strong episodes of high-energy (400–1000 keV) emission were observed on four separate occasions during the first 84 days of the event (Fig. 1, panels 5 and 6). This corresponds to $0–0.70$ phase of the 120 day period, which was first suggested by Iyudin & Haberl (2001) based on several years of COMPTEL observations. COMPTEL results...
showed that the 1.5–2 MeV emission was primarily confined to 0–0.5 phase of the 120 day period.

6. The averaged high-intensity spectrum above 300 keV obtained on TJD 8841–8865 is softer than the average low-intensity power-law spectrum (TJD 9010–9040), and intercepts the latter at ∼600 keV (Fig. 5).

7. Several key features displayed by GRO J0422+32 spectra are remarkably similar to those seen in Cyg X-1, suggesting that similar processes may be at work in both systems. A direct comparison of these features is shown in Table 2.

The two-component Compton plus power-law spectrum observed in GRO J0422+32, Cyg X-1, and several other black hole binaries has been the subject of several theoretical studies in recent years. Earlier works in interpreting the Cyg X-1 spectra below ∼1 MeV in terms of a two-region core/corona thermal model (Ling et al. 1997; Skibo & Dermer 1995) using the Monte Carlo approach have had some degree of success. However, we have now seen persistent power-law emission extended to ∼1 MeV in both the high- and low-intensity γ-ray state spectra of GRO J0422+32, as shown in this and other papers (Grove et al. 1998; van Dijk et al. 1995; Iyudin & Habert 2001), and in the γ₀ (high/soft) and γ₂ (low/hard) spectra of Cyg X-1 (Ling et al. 1997; McConnell et al. 2000, 2002). These results suggest that the high-energy power-law component cannot be adequately interpreted in terms of pure thermal processes alone, and that nonthermal processes must be also at work in these systems.

The power-law spectral tail may be associated with dynamical Comptonization processes in flows converging onto a black hole (Laurent & Titarchuk 1999; Turolla, Zane, & Titarchuk 2002). Turolla et al. (2002) showed that a power-law photon index of less than 3 can be produced by upscattering of primary photons off infalling electrons. However, no direct comparison between theoretical predictions and observational data can be obtained at this time. Nonthermal γ-ray emission may be also associated with jets, which was discussed by Meier (2001) as a natural consequence of accretion flows onto rotating black holes. A relativistic jet in Cyg X-1 has been observed in the radio band (Stirling et al. 2001; Fender et al. 2000; Fender 2001) when the source was in the γ₂ (low/hard) state. Radio emission was also seen in GRO J0422+32 (Shrader et al. 1994), although no jetlike structure was resolved from these observations.

A more general approach using a hybrid thermal/nonthermal Comptonization model (EQPAIR) was proposed by Coppi (1998; see also Gierlinski et al. 1999). In this model, the electron distribution consists of a Maxwellian component with a temperature, kT, plus a nonthermal power-law component. The acceleration of nonthermal electrons is independently taking place but is coupled to the background thermal plasma by Compton scattering and Coulomb collision processes. The model basically allows for both thermal and nonthermal Comptonization of soft photons, as well as pair production, Compton reflection, and bremsstrahlung emission.

Although we do not know with certainty at present the processes producing the nonthermal power-law γ-ray emission (e.g., jets or other processes), our data suggest that nonthermal power-law emission was present throughout the outburst. It was fully visible in the 35 keV to 1 MeV energy band when the GRO J0422+32 was in the low-intensity state, and only partially visible in the 313 keV to 1 MeV band when it was in the high-intensity state. Furthermore, the average spectral index for the former was harder (∼2) than the latter (∼3–5).

We suggest a possible scenario for interpreting the observed data that includes a separate nonthermal (perhaps a jetlike) source region in the ADAF model of Esin et al. (1998), along with the source geometry envisioned by Poutanen & Coppi (1998) and others (Coppi 1998; Fender & Kuulkers 2001; Zdziarski et al. 2002) (see Fig. 6). In this scenario, during the high-intensity state (or γ₂ state for Cyg X-1; Fig. 6, right panel), the system consists of a hot inner corona, a cooler outer thin disk, and a region that produced the variable power-law γ-ray emission. Under this condition, the transition radius of the disk is ∼100 Schwarzschild radii from the black hole. Electrons in the hot corona upscattered the low-energy photons both produced inside the corona and from the outer disk to form the Comptonized component that dominates the spectrum in the 35–300 keV range. They also downscattered the high-energy photons (>10 MeV) produced in the “jet” region, resulting in the formation of a softer power-law component observed in the 300 keV to 1 MeV range compared to that observed in the low-intensity spectrum.

When the source was in the low-intensity soft γ-ray state (or γ₀ state for Cyg X-1) due probably to a significantly increase of the accretion rate, a large soft flux was produced in the disk that effectively quenched and cooled the inner corona, and moved the transition radius inward to a distance
very close to the horizon (Fig. 6, left panel). Under this condition, the Comptonized component in the 35–300 keV range diminishes, and the source spectrum is dominated by the unperturbed power-law emission produced in the jetlike nonthermal source region with a characteristic index of $\sim 2$.

While the above scenario helps to interpret some aspects of the new observational features, there are several issues that are not yet resolved: (1) What is the cause for the time-lag effect of a few days seen between the low-energy ($<200$ keV) and high-energy ($>200$ keV) photons? Is this an indication of the response time for the Comptonization process in the system to a sudden change of the accretion rate? (2) The hard high-energy (0.3–1 MeV) spectral component observed in VP 42 with an index of $\sim 1$ is strongly reminiscent of the “MeV bump” seen in the $\gamma$ spectrum of Cyg X-1 (Ling et al. 1987). Is this caused by a intrinsic change in the nonthermal emission, or is it a signature of the pair plasma (Liang & Dermer 1988; Ling & Wheaton 1989; Poutanen & Coppi 1998) produced by heating the corona to a very high temperature ($\sim 10^9$ K)? Such heating could be caused by a further reduction of the accretion rate that led to the reduction of soft photons for its cooling. (3) The intensity of the radio emission was observed to track the gamma rays throughout the outburst for GRO J0422+32 (Shrader et al. 1994), but was only seen in the $\gamma_2$ state (and not the $\gamma_0$ state) of Cyg X-1 (Stirling et al. 2001; Fender et al. 2000; Fender 2001). What is the reason for this difference? Is it caused by a difference of the “beaming” effect in the two systems? We hope that these results will stimulate further theoretical and observational investigations in the future of this very unusual and exciting black hole candidate discovered by BATSE.

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Fig. 6.—Simple sketch of the system by including a jetlike region that produced the nonthermal $\gamma$-ray emission in the ADAF model of Esin et al. (1998), along with the source geometry envisioned by Poutanen & Coppi (1998) and others (Coppi 1998; Fender & Kuijkers 2001; Zdziarski et al. 2002). During the high-intensity state (right panel), the system consists of a hot inner corona, a cooler outer thin disk, and a jetlike region that produced the variable power-law $\gamma$-ray emission. Under this condition, the transition radius of the disk is $\sim 100$ Schwarzschild radii from black hole. Electrons in the hot corona upscatter the low-energy photons both produced inside the corona and from the outer disk to form the Comptonized component observed in the 30–300 keV range. The same electrons also downscatter the high-energy power-law photons produced in the “jet” region, resulting in the formation of a softer power-law component observed in the 300 keV to 1 MeV range compared to that observed in the low-intensity spectrum. During the low-intensity state, due probably to a significantly increase of the accretion rate, a large amount of soft photons produced in the disk effectively cool and quench the corona, and move the transition radius inward to a distance very close to the horizon (left panel). Under this condition, the Comptonized component in the 30–200 keV range diminishes, and the soft $\gamma$-ray spectrum is therefore dominated by the unperturbed nonthermal emission in the jetlike region with a characteristic power-law index of $\sim 2$. 

412 LING & WHEATON Vol. 584
No. 1, 2003  BATSE SOFT γ-RAY OBSERVATIONS OF GRO J0422+32  413

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