Galactic Black Hole Binaries: High-Energy Radiation

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Abstract. Observations of galactic black hole candidates made by the instruments aboard the Compton GRO in the hard X-ray and γ-ray bands have significantly enhanced our knowledge of the emission properties of these objects. Understanding these observations presents a formidable challenge to theoretical models of the accretion flow onto the compact object and of the physical mechanisms that generate high-energy radiation. Here we summarize the current state of observations and theoretical interpretation of the emission from black hole candidates above 20 keV.

The all-sky monitoring capability of BATSE allows, for the first time, nearly continuous studies of the high-energy emission from more than a dozen black hole candidates. These long-term datasets are particularly well-suited to multiwavelength comparison studies, from the radio upward in frequency (Zhang et al. 1997a, these proceedings). Energy spectral evolution and/or spectral state transitions have been observed from many of the black hole candidates. Moderately deep searches of the galactic plane suggest a deficit of weak γ-ray transients. Such population studies have implications for the origin of black hole binaries and the nature of accretion events.

Observations above 50 keV from OSSE demonstrate that in the γ-ray band there exist two spectral states that appear to be the extensions of the X-ray low (hard) and high (soft), or perhaps very high, states. The former state, the "breaking" state, cuts off with e-folding energy $\sim$100 keV and has its peak luminosity near this energy; thus substantial corrections need to be made to historical estimates of the bolometric luminosity of black holes in the "low" state. In contrast, in the X-ray high (soft) state, the luminosity peaks in the soft X-rays and the spectrum extends with an unbroken power law, even up to energies above 500 keV in some cases. COMPTEL has detected emission above 750 keV from Cyg X-1 and the transient GRO J0422+32. In both cases the data suggest that an additional weak, hard spectral component is required beyond that observed by OSSE at lower energies, although the precise spectral form is

yet to be determined.

The breaking γ-ray spectrum can be well modeled by Comptonization of soft photons from the accretion disk in a hot thermal plasma. However, recent studies of the combined X-ray and γ-ray spectrum of Cyg X-1 and GX339–4 cast severe doubts on the simple geometry of a hot corona overlying a thermal accretion disk. Furthermore, timing studies of the former source are inconsistent with spectral formation by Compton scattering in a uniform, compact hot cloud, suggesting instead a decline in electron density with increasing radius. The power-law γ-ray spectral state creates more significant theoretical challenges, particularly in explaining the lack of a break at energies exceeding the electron rest mass. It has been suggested that in the X-ray high (soft) state, the high-energy emission arises from bulk-motion Comptonization in the convergent accretion flow from the inner edge of the accretion disk. Such a process can conceivably generate the γ ray spectrum extending without a cutoff, if the accretion rate approaches that of Eddington.

I   INTRODUCTION

The most reliable evidence for the presence of a black hole in a binary system comes from determination of a mass function through optical measurements of the radial velocity of the companion star. If the resulting lower limit on the mass of the compact object exceeds $3\,\mathrm{M_\odot}$, the upper limit for the mass of a stable neutron star based on current theory, then one can reasonably assume that the compact object is a black hole. There are at least nine X-ray binary systems with minimum mass estimates exceeding $3\,\mathrm{M_\odot}$, of which three (Cyg X-1, GRO J0422+32, and GRO J1655–40) have been clearly detected by GRO instruments. Other objects are identified as BHCs based on the similarity of their high-energy spectra and rapid time variability to those of Cyg X-1. Such classification is, of course, somewhat tenuous. Before neutron stars and black holes can be reliably distinguished based on their X-ray and γ-ray spectra, the full range of spectral forms from both classes must be observed and characterized. Extensive knowledge of the X-ray emission of these objects has accumulated in the literature, but the broad nature of the γ-ray emission is only now coming to light, with the high sensitivity of current-generation instruments.

The instruments of the Compton GRO have made extensive observations in the hard X-ray and γ-ray bands of galactic black hole candidates (BHCs). With its all-sky capability, BATSE has monitored emission on a nearly continuous basis from at least three persistent sources (Cyg X-1, 1E1740.7–2942, GRS 1758–258) and eight transients (GRO J0422+32, GX339–4, N Mus 1991, GRS 1716–249, GRS 1009–45, 4U 1543–47, GRO J1655–40, and GRS 1915+105). Lightcurves are presented below in Fig. 2. OSSE has made higher-sensitivity, pointed observations of all of these sources, spectra of which appear below in Fig. 1. COMPTEL has detected emission above 750 keV from

Cyg X-1 and GRO J0422+32. To date, there have been no reported detections of galactic BHCs by EGRET.

The French coded-aperture telescope Sigma on the Russian Granat spacecraft has imaged at least a dozen BHCs, including most of those in the list above, but with the addition of TrA X-1, GRS 1730–312, and GRS 1739–278. The latter two objects were weak transients discovered during a multi-year survey of the galactic center region and have been classified as BHCs by their outburst lightcurves and the hardness of their spectra (Vargas et al. 1997). In this survey, Sigma regularly detected the persistent, variable sources 1E1740.7–2942 and GRS 1758–258, both of which are classified as BHCs on spectral grounds. The most striking result from Sigma observations of BHCs is the detection of broad spectral features below 500 keV from 1E1740.7–2942 (Sunyaev et al. 1991, Bouchet et al. 1991, Churazov et al. 1993, Cordier et al. 1993) and N Mus 1991 (Goldwurm et al. 1992, Sunyaev et al. 1992). These features have been interpreted as thermally broadened and red-shifted annihilation radiation from the vicinity of the compact object.

II   BATSE SURVEY FOR BLACK HOLE BINARIES IN THE GALACTIC PLANE

BATSE has proven to be a remarkably effective tool for the study of persistent and transient hard X-ray sources using the occultation technique. Not only can known sources be studied, with sensitivity of $\sim$100 mCrab for a 1-day integration (Harmon et al. 1992), but the powerful occultation imaging technique (Zhang et al. 1993) has opened the way for the study of relatively crowded fields and previously unknown sources. Grindlay and coworkers have begun a survey of the galactic plane with the objective of measuring or constraining the black hole X-ray binary (BHXB) population in the Galaxy. BHXBs, both those with low mass companions (e.g. the X-ray novae such as N Muscae 1991) and the high mass systems such as Cyg X-1, are distinguished by having relatively luminous hard X-ray (20–100 keV) emission as compared to the systems containing neutron stars (Barret et al. 1996a). Thus a survey for persistent or transient sources in the hard X-ray band is optimally suited for the detection and study of BHXB systems. Furthermore, since most BHXBs are now known to be transient—and indeed the X-ray novae have allowed the most convincing dynamical mass function measurements of the optical counterparts when they are in quiescence (cf. van Paradijs and McClintock 1995)—the transients are the systems most likely to be BHXBs (and see van Paradijs 1996 for a likely explanation).

Given the recurrence times of the prototypical soft X-ray transients (SXTs) to be $\gtrsim$10-50 years (e.g. $\gtrsim$10 years for Nova Muscae; cf. Barranco and Grindlay 1997), and the relatively nearby (1–4 kpc) optical distances for the bright SXTs identified at a rate of $\sim$1 per year by Ginga, WATCH and BATSE,

it is straightforward to extrapolate that 3–4 per year should be detectable by BATSE in these deeper searches (i.e. with peak fluxes at or below 100 mCrab) if the BHXBs are distributed uniformly in a galactic disk with radius 12 kpc. Thus over the 6 years of archival BATSE data now available, a full analysis of the galactic plane should yield a significant number ($\gtrsim 20$) of new BHXBs.

The CfA BATSE Image Search (CBIS) system (Barret et al. 1997, Grindlay et al. 1997) has been run on 900d of BATSE data. Known sources, though perhaps not previously detected by BATSE (e.g. Cir X-1; Grindlay et al. 1997) are found in the survey. Both short-outburst BHXBs (e.g. 4U1543–47) and longer duration outburst from neutron star LMXBs (e.g. 4U1608–52) have been found in the data "automatically" at the times and approximate fluxes seen with direct occultation light curve analysis (Harmon et al. 1992). More importantly, the search has yielded at most 5 candidate new (i.e. uncatalogued) sources. All of these candidate sources are below $\sim$50–100 mCrab in peak flux; no new transients at $\sim$100–200 mCrab have been found in this initial survey. The preliminary results thus suggest, but do not yet prove, a lower rate of candidate new BHXB transients than the simple scalings above would suggest: a rate of $\sim$1–2 per year rather than the 3–4 possibly expected.

If the true number is in fact much less than expected, then important questions arise for the BHXB population and/or transient outburst models:

1. *What is the total number of BHXBs?* Many authors (e.g. Tanaka and Lewin 1995 and references therein) estimate on the basis of simple arguments (such as the SXT detection rate) that the total population of low-mass BHXBs in the galaxy is $\gtrsim$300–1000. If BATSE cannot find the predicted fainter systems, have the optical distances been systematically under-estimated or are the peak luminosities typically fainter?

2. *What is the formation rate of BHXBs?* Clearly, a measurement of, or constraints on, the total number of BHXBs is needed to determine if models for the formation of BHXBs vs. neutron star binaries (e.g. Romani 1992) that predict large numbers of low-mass BHXBs are correct.

3. *What are the characteristic spectra and lightcurves of SXTs?* A search for faint BHXBs with BATSE (and future more sensitive surveys) is crucial for comparison with ASM or WFC searches (RXTE and future ASMs) which will typically operate in the 2–10 keV band. Recent WFC detections of $\sim$10 mCrab transients in the galactic bulge region by SAX (e.g. in 't Zand and Heise 1997) may suggest a much higher rate of either fainter or softer transients.

4. *What are the characteristic recurrence times for SXTs?* If the BATSE detection rate is much lower than predicted, is the recurrence time much longer than the small-N statistics would now indicate? This of course directly affects questions 1 and 2 above as well as the outburst models. It is of particular interest to search for "mini"-outbursts of the nearby bright systems (e.g. A0620–00), which might be expected to be more detectable in the hard X-ray band than the soft band in the low (hard) state (cf. Fig. 1).

III TWO GAMMA-RAY SPECTRAL STATES

The historical record of X-ray (i.e. <30 keV) observations of galactic BHCs reveals at least four spectral states (see, e.g., Tanaka 1989 & 1997, Grebenev et al. 1993, and van der Klis 1994 & 1995). In the "*X-ray very high*" and "*X-ray high (soft)*" states, the X-ray spectrum is dominated by an "ultrasoft" thermal or multi-color blackbody component with kT $\sim$ 1 keV. A weak power-law tail, with photon number index $\Gamma \sim$ 2–3, is frequently present and dominant above $\sim$10 keV. The states differ in X-ray luminosity—the former being close to the Eddington limit, L_E, and the latter typically $\sim$3–30 times less than L_E—and in the character of their rapid time variability—the very high state usually has 3–10Hz quasi-periodic oscillations (QPOs) and stronger broad-band noise. The "*X-ray low (hard)*" state exhibits a single power-law spectrum with $\Gamma \sim$ 1.5–2, and a typical X-ray luminosity of <1% of Eddington. Recent measurements by OSSE indicate that, in this state, the γ-ray luminosity of a typical BHC exceeds the X-ray by a factor $\sim$5 (Grove et al. 1997b). This state is characterized by strong, rapid, intensity variability, with rms variations of order a few tens of percent of the total emission. The "*X-ray off*" or "*quiescent*" state exhibits very low level emission with uncertain spectral shape at a luminosity $L_X < 10^{-4} L_E$.

OSSE observations of a number of transient BHCs (Grove et al. 1997a, 1997b) indicate that there are at least two distinct γ-ray spectral states, the "*breaking*" state, which corresponds to the X-ray low (hard) state, and the "*power law*" state, which corresponds to the X-ray high (soft) state or very high state. The identification of the breaking state with the low (hard) state is quite firm but, because of the paucity of simultaneous X-ray and γ-ray observations, the identification of the power law state with which of the two high states is less certain. It is clear, though, that the presence of a strong soft excess at least some of the time during an outburst is a requirement for the γ-ray power law state to be observed. Fig. 1 shows photon number spectra from OSSE for seven transient BHCs, along with the best-fit analytic model extrapolated down to 10 keV and contemporaneous X-ray data if they are available. The two spectral states are readily apparent.

Sources in the X-ray low (hard) [i.e. breaking γ-ray] state typically have an X-ray index $\Gamma \sim$ 1.5, begin breaking from the power law at $E_b \sim$ 50 keV, and cut off with exponential folding energy of $E_f \sim$ 100 keV. The bulk of the luminosity in this state is emitted near 100 keV. Indeed the spectra of GRO J0422+32 and GRS 1716–249 indicate that the luminosity above 50 keV (or 10 keV) exceeds that in the 0.5–10 keV band by a factor of $\simeq$4 (or $\simeq$6).

Sources in the γ-ray power-law state have a strong ultrasoft excess above a single power-law spectrum, with $\Gamma \sim 2.5 - 3.0$ and no evidence for a high-energy break, even at energies exceeding $m_e c^2$. No spectral features (e.g. narrow or broad lines) are apparent near or above 511 keV, as would be
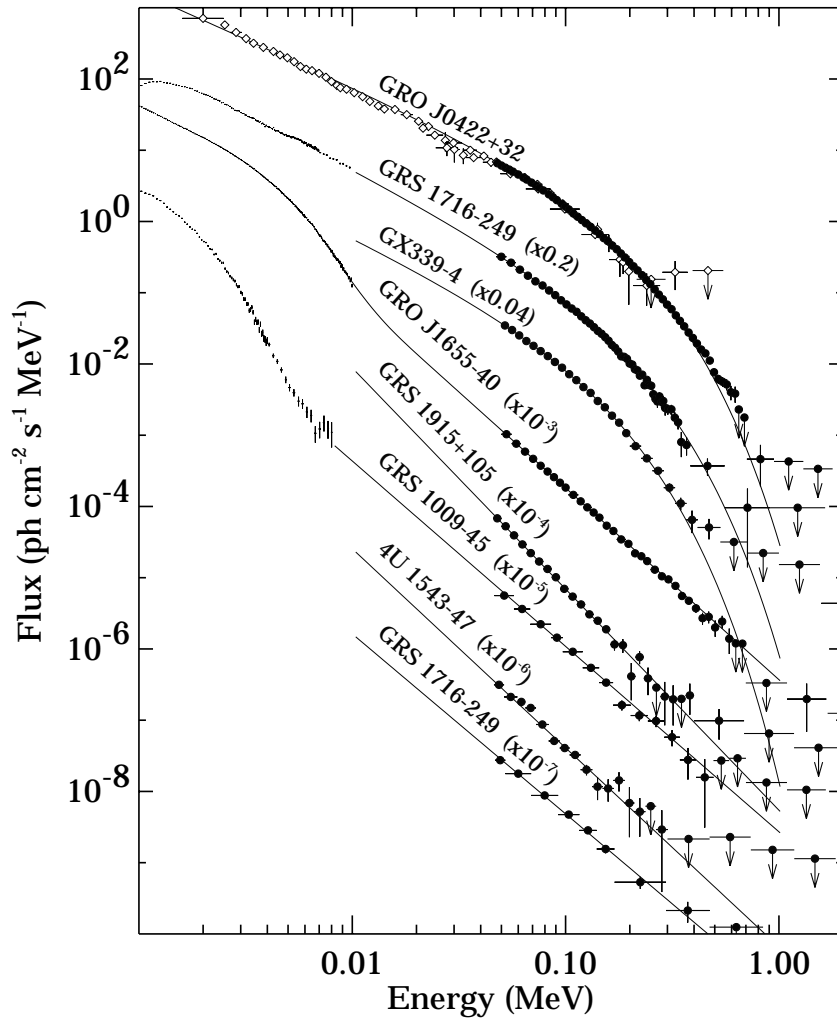
FIGURE 1. Photon number spectra from OSSE for seven transient BHCs. Spectra are averaged over all observing days for which there was detectable emission and, for clarity of the figure, have been scaled by arbitrary factors as indicated. Two spectral states are apparent. Contemporaneous TTM and HEXE data (open diamonds) and ASCA data (crosses) are shown for GRO J0422+32 and GRS 1716–249, respectively. Non-contemporaneous ASCA data (crosses) are shown for GRS 1009–45 and GRO J1655–40. ASCA data for GRS 1716–249 and GRS 1009–45 are from Moss (1997). Figure is from Grove et al. (1997b).

expected from standard nonthermal Comptonization models (Blumenthal & Gould 1970, Lightman & Zdziarski 1987). In this state, L_γ is only a fraction of the X-ray luminosity. The strong ultrasoft component is the signature of either the X-ray very high or high (soft) state, although the generally weak or absent *rapid* time-variability (<1 sec) suggests that the association is with the high (soft) state (Grove et al. 1997b). As a caveat, we note that there indeed can be a degree of independence of the ultrasoft and power-law spectral components exhibited in the long-term temporal behavior of the broadband emission: for example, while recent RXTE observations (Greiner, Morgan, & Remillard 1996) of the galactic superluminal source GRS 1915+105 demonstrate that the X-ray intensity is dramatically variable on timescales of tens to thousands of seconds, showing several repeating temporal structures, the γ-ray emission is steady and only slowly evolving (Grove et al. 1997b).

Recent observations of Cyg X-1 reveal a bimodal spectral behavior in the γ-ray band as well as the X-ray band (Phlips et al. 1996), equivalent to the above, and confirming the identification of X-ray and γ-ray states (Gierlinski et al. 1997; Phlips et al. 1997). These observations are discussed in greater detail below.

The transient GRS 1716–249 is shown twice in Fig. 1, apparently having undergone a spectral state change late in its second outburst (Moss 1997, Grove et al. 1997b). As is the case for Cyg X-1 (Phlips et al. 1996), the power-law state has lower L_γ than the breaking state. How the *bolometric* luminosity changes is less certain and will require further simultaneous broadband observations.

BATSE hard X-ray (20–100 keV) lightcurves for the same seven transient BHCs plus N Mus 1991 are shown in Fig. 2. Harmon et al. (1994) identified two types of transients based on such lightcurves. The first type has a relatively fast rise followed by a more gradual, decaying flux envelope after the initial outburst, and secondary maxima a few weeks to months into the decline. The decay sometimes approaches an exponential form as seen in the soft X-ray band (Tanaka and Lewin 1995). The rise and decay times vary over a broad range, but are order of a few days and few tens of days, respectively. The second type has a longer rise time (of order weeks) and multiple, recurrent outbursts of highly variable duration. Major outbursts tend to be of similar intensity, with active periods lasting for several years. GRO J0422+32, N Mus 1991, GRS 1009–45 and 4U 1543–47 are of the first type, and GRS 1915+105 and GX339–4 are of the second type. GRS 1716–249 (=GRO J1719–24) and GRO J1655–40 seem to share properties of both types. No coherent, long-term periodicities in the high energy emission have been seen in either type of transient. There appears to be no correlation between the lightcurve type and the spectral state.

Elsewhere in this volume, Zhang et al. (1997a) report the detection of both γ-ray spectral states from 1E1740.7–2942, the persistent BHC near the galactic center. The breaking γ-ray state has higher L_γ than the power law
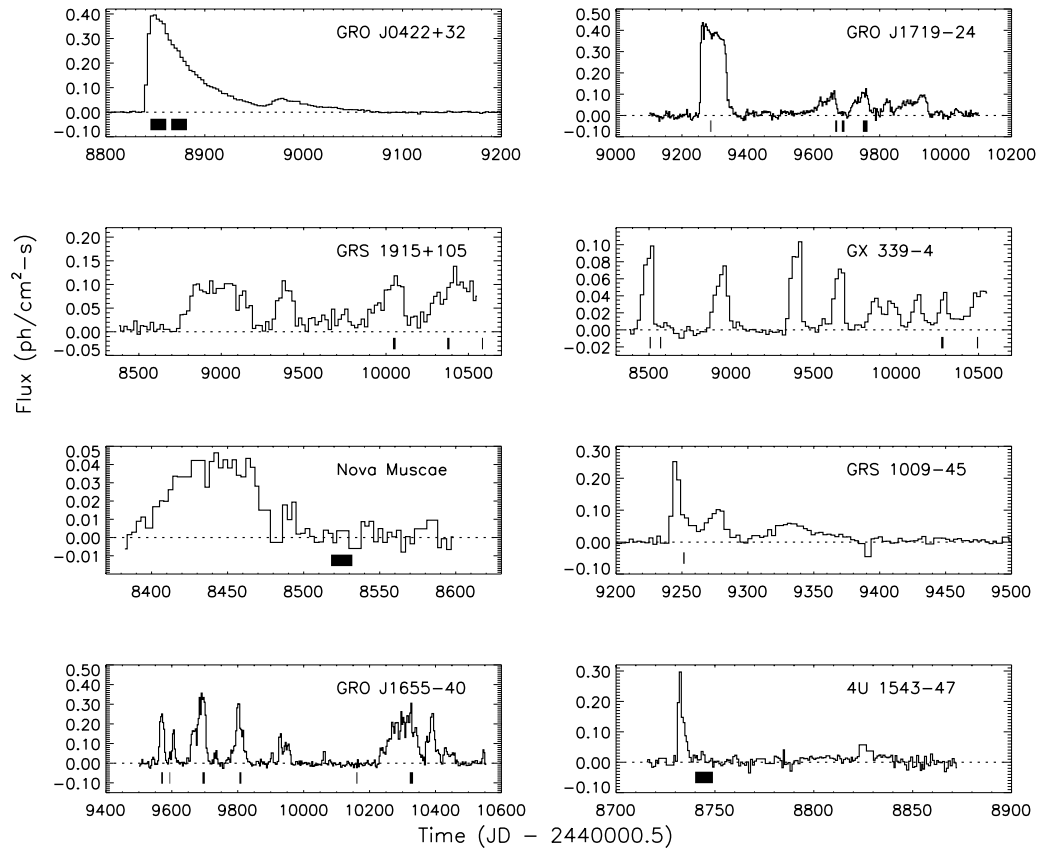
FIGURE 2. Lightcurves of transient black hole binary systems in the 20–100 keV band detected with BATSE. OSSE observing times are shown as bold solid lines along the horizontal (time) axis. All light curves include the primary and secondary outbursts until mid-1997, except for N Mus 1991. Its primary outburst occurred prior to launch of CGRO.
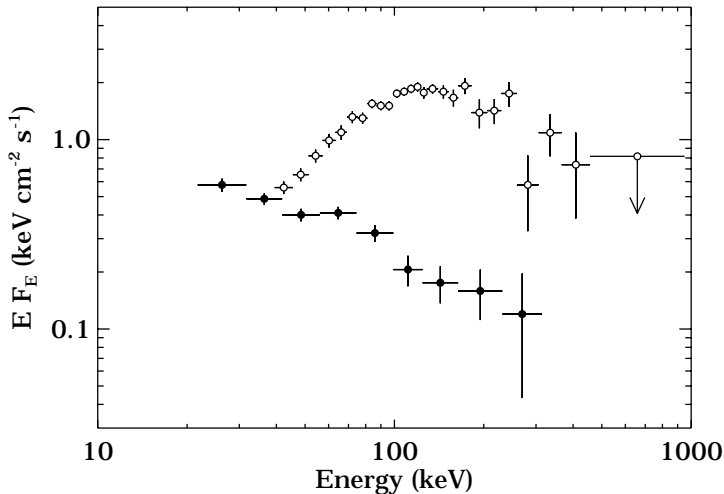
FIGURE 3. Spectra of 1E1740.7-2942 in the γ-ray breaking state (open circles; OSSE) and power-law state (solid circles; BATSE). The OSSE data have been corrected for nearby point sources and diffuse emission.

state. They also report the detection of two luminosity states in GRS 1758–258, but because of the relative faintness of the source, do not present any spectral analysis. In Fig. 3 we have plotted the spectrum of 1E1740.7–2942 in the low-luminosity, power-law state from BATSE (adapted from Zhang et al.) and the high-luminosity, breaking state from OSSE. Because neither BATSE nor OSSE is an imaging instrument, both measurements are subject to contamination from the bright diffuse galactic continuum emission and nearby point sources. To minimize this potential source of error, the BATSE data were collected when the limb of the earth was at large angles to the galactic plane, so that the galactic ridge component would not produce any occultation modulation (S.N. Zhang, private communication). The OSSE spectrum shown is the result of a simultaneous fit to several known point sources, which were reasonably well separated by scanning the OSSE detectors along the ecliptic, and we have subtracted an estimate of the diffuse emission derived from an extensive series of galactic-center region mapping observations (G.V. Jung, private communication).

IV   BROADBAND OBSERVATIONS AND SPECTRAL MODELING

In recent years, substantial progress has been made in our understanding of the environment of accreting black holes and the physical processes that drive the high-energy emission. Indeed the breaking γ-ray state can be relatively
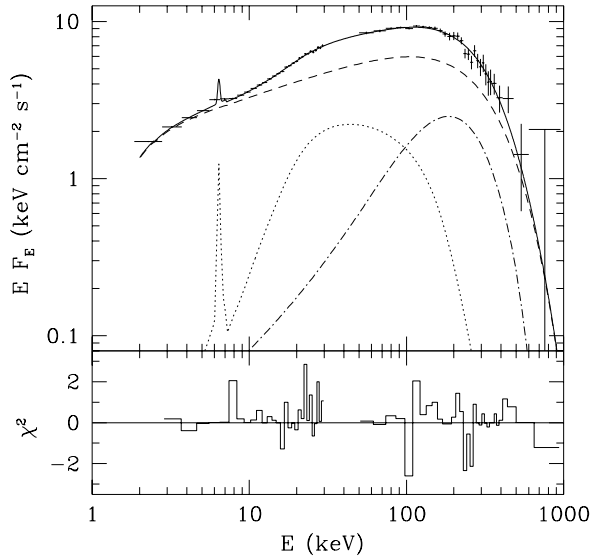
FIGURE 4. Broadband spectrum of Cyg X-1 observed simultaneously by ASCA & OSSE. Two-temperature thermal Comptonization model (dashed and dot-dashed curves), along with Compton reflection (dotted curve). Bottom panel gives contribution to total χ^2. From Gierlinski et al. (1997).

well modeled by Comptonization of soft photons from the accretion disk in a hot thermal plasma, with the plasma temperature determined by the cutoff energy. In some cases, additional spectral components are required which can be understood as effects of the hard radiation scattering off relatively cold electrons (for example as a reflection off a cold accretion disk or the transmission of the hard radiation through a cold medium surrounding the compact source). The nature and geometry of the Comptonizing plasma is, however, highly debatable, and recent studies of the combined X-ray and γ-ray spectrum and temporal properties of Cyg X-1 indicate that a simple, slab geometry for the corona is implausible.

Simultaneous, broadband spectral measurements are especially powerful in elucidating the physical processes that drive the high-energy emission of BHCs. Two recent broadband studies, one from Ginga and OSSE observations of Cyg X-1 (Gierlinski et al. 1997) and the other from ASCA and OSSE observations of GX339–4 (Zdziarski et al. 1997), are the most detailed investigations to date on BHCs in the X-ray low (hard) state.

In the low (hard) state, the X-ray spectrum of Cyg X-1 consists typically of a power law with photon number index $\Gamma \sim 1.6 - 1.7$ and a Compton-reflection component that significantly affects the continuum above 10 keV and includes

near 7 keV both an Fe K edge and an Fe Kα fluorescence line (Ebisawa et al. 1996 and references therein). The low-energy gamma-ray spectrum is steeply cut off above $\sim$150 keV and, while L_γ varies by a factor of at least several in this state, the spectral parameters vary only weakly (Phlips et al. 1996). The X-ray (Ueda et al. 1994) and γ-ray (Grabelsky et al. 1995) spectra of GX339–4 in the low (hard) state are generally quite similar in form to those of Cyg X-1.

For both Cyg X-1 and GX339–4, the combined X-ray and γ-ray spectrum was modeled by thermal Comptonization in a spherical cloud with an isotropic source of soft seed photons from a blackbody distribution, as described in Zdziarski, Johnson, & Magdziarz (1996). The parameters of the hot plasma are the temperature, kT, and the X-ray photon number index, Γ, which is related to the Thomson optical depth, τ, of the Comptonizing plasma. The model allowed for Compton reflection with reflector solid angle Ω, and an Fe Kα line. An additional soft X-ray blackbody component was required below 3 keV from both sources; this component is likely to originate in a cold accretion disk in the vicinity of the hot Comptonizing plasma. This same cold disk would then also be responsible for the Compton reflection component. In the case of Cyg X-1, the spectrum cut off above 100 keV too sharply for an isotropic, single-temperature Comptonization model, so Gierlinski et al. (1997) added a Wien-like component from an optically-thick plasma at $kT \sim 50$ keV, speculating that it is the signature of a transition region between the hot and cold media in the accretion flow.

As shown in Fig. 4 and 5, these complicated, multi-parameter models give an excellent description of the X-ray and OSSE data in the entire energy range, from $\sim$2 keV to $\sim$1 MeV. The time-averaged spectrum of Cyg X-1 has been measured by COMPTEL out to several MeV (McConnell et al. 1997). A comparison with contemporaneous data from both OSSE and BATSE has so far yielded only limited insights because of discrepancies among the spectra from the three instruments. While the nature of these discrepancies is still being investigated, they may result merely from a difference in absolute flux normalization. In any case, it is becoming clear that the emission above 1 MeV implies more than a simple Comptonization process. A similar conclusion can be drawn from COMPTEL results for GRO J0422+32 (van Dijk et al. 1995).

For both Cyg X-1 and GX339–4, the description of Gierlinski et al. (1997) and Zdziarski et al. (1997) rules out a geometry with a corona above the surface of an optically-thick disk (Haardt & Maraschi 1993; Haardt et al. 1993). The solid angle Ω of the reflector is only 30–40% of the 2π expected for a corona above a flat disk. Furthermore, the intrinsic spectrum is so hard that the flux of the incident seed photons is about an order of magnitude less than the Comptonized flux (i.e. the source is "photon starved"), whereas the seed photon Comptonized photon fluxes are almost the same in the disk-corona model (Haardt & Maraschi 1993). In addition for Cyg X-1, the narrowness of the Kα line observed by ASCA (Ebisawa et al. 1996) implies that the
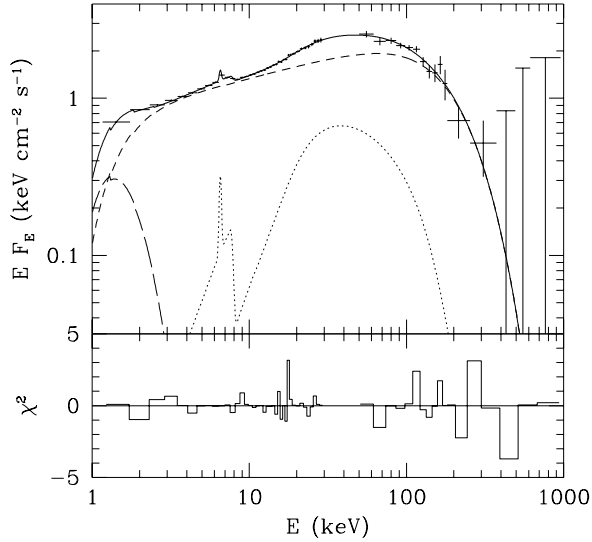
FIGURE 5. Broadband spectrum of GX339–4 observed simultaneously by Ginga & OSSE on 1991 Sep 11. Model consists of blackbody radiation (long dashes) as seed for thermal Componization in hot plasma (short dashes), which is Compton reflected from the disk (dotted). Bottom panel gives contribution to total χ^2. From Zdziarski et al. (1997).

reflecting medium is cold and therefore likely far from the central black hole. On the other hand, the fits *can* correspond to a geometry with a hot inner disk surrounded by a colder outer disk. The hot disk is geometrically thick and irradiates the outer cold disk. The irradiation gives rise to the Compton-reflection component with small Ω, and accounts for the modest blackbody emission of the disk observed at low energies.

There are currently no high-sensitivity, *simultaneous* X-ray and γ-ray studies in the literature for the X-ray high (soft) state, although several simultaneous datasets from RXTE and GRO exist for the superluminal sources GRO J1655–40 and GRS 1915+105. A simultaneous ASCA and BATSE observation of GRO J1655–40 *has* been published (Zhang et al. 1997b), which shows a strong ultrasoft excess and a soft power-law tail ($\Gamma \simeq 2.4$) extending beyond 100 keV.

The physical processes driving the hard emission in the X-ray high (soft) state are less well determined. It is generally well agreed upon that the ultrasoft component, which can be described by a multi-color disk blackbody spectrum (Mitsuda et al. 1984), is thermal emission from an optically thick and geometrically thin accretion disk roughly in the region $10^7 < r < 10^9$ cm from the black hole. The power-law tail seen by Ginga from a number of BHCs

in the high (soft) state (e.g. GX339–4: Makishima et al. 1986) was ascribed to thermal Comptonization in the hot ($kT \sim 60$ keV) inner disk region. This interpretation is ruled out by Sigma observation of GX339–4 in this state with a spectrum that extends unbroken to at least 100 keV (Grebenev et al. 1993), well beyond the break for a Comptonized spectrum of this temperature. The unbroken power laws observed by OSSE from a number of other BHCs require temperatures of at least several hundred keV.

Ebisawa, Titarchuk, & Chakrabarti (1996) propose that the high-energy emission in the high (soft) state arises from bulk-motion Comptonization of soft photons in the convergent accretion flow from the inner edge of the disk. In the high (soft) state, the copious soft photons from the disk cool the electrons efficiently in the inner, advection-dominated region, and Comptonization due to bulk motion dominates over that due to thermal motion. In contrast, in the low (hard) state, there are fewer soft photons, hence higher temperatures in the Comptonization region (i.e. $\sim$50–100 keV, rather than $\sim$1 keV), and thermal Comptonization dominates. Calculations by Titarchuk, Mastichiadis, & Kylafis (1996) indicate that the bulk-Comptonization spectrum can continue unbroken well beyond $m_e c^2$, as is observed at least in the case of GRO J1655–40.

The detection of Compton reflection in the high (soft) state may prove to be a complication (A. Zdziarski, private communication). Compton reflection is clearly seen in the low (hard) spectrum of a number of sources, and is detected in both *spectral states* in N Mus 1991 (Ebisawa et al. 1994) and Cyg X-1 (Gierlinski et al. 1997). In the latter objects, the reflection parameter Ω approaches 2π in the high (soft) state, indicating that the source of the hard photons completely covers the reflector, e.g. the cool disk. The bulk-Comptonization model postulates an advecting, Thomson-thick medium above the disk, and it is in this advecting medium that the Comptonization takes place. However, because it is optically thick, the reflected component is trapped in the advecting flow and does not escape to the observer. Thus detection of reflection in the high (soft) state would cast doubt on the application of bulk Comptonization in these objects.

V   THE SEARCH FOR LINE EMISSION

Transient, broad emission lines have been reported in the literature from Cyg X-1 (the "MeV bump"), 1E1740.7–2942, and N Mus 1991. In the latter two cases, the lines have been interpreted as red-shifted and split (due to disk rotation) annihilation features. The very high sensitivity of the GRO instruments relative to previous gamma-ray telescopes makes deep searches for such lines possible on many timescales. Long-term observations of Cyg X-1, by both COMPTEL and OSSE, at a range of hard X-ray intensities set strict upper limits on the magnitude and duty cycle of a possible MeV bump.

The upper limits are more than an order of magnitude below the historical reports (Phlips et al. 1996, McConnell et al. 1994). Similarly, searches by Grove et al. (1997b) through hundreds of days of BHXB observations by OSSE have revealed no evidence for transient red-shifted annihilation lines at levels approaching those in the literature. For example, a broadened 480 keV line at 6×10^{-3} ph cm^{-2} s^{-1}, the intensity reported from N Mus 1991 by Sigma (Goldwurm et al. 1992, Sunyaev et al. 1992), would have been detected by OSSE at $\sim 40\sigma$ in an average 24-hour period.

In general these transient events are reported by a single instrument and cannot be confirmed or refuted because no other instrument is observing at the same time. However, the broad-line excess from 1E1740.7–2942 in 1992 Sep reported by Sigma (Cordier et al. 1993) is *not* confirmed by OSSE (Jung et al. 1995), which by chance was viewing the galactic center region before, during, and after the event. Confirmation of such transients would provide strong support for pair plasma models of black hole radiation, lending credence to the suggestion (e.g. Ramaty et al. 1994) that sources such as 1E1740.7–2942 might be significant sources of positrons in the central region of our galaxy.

VI   RAPID VARIABILITY AND PHASE LAGS

Strong, rapid, aperiodic variability (i.e. on timescales of tens of seconds or less) is frequently reported in X-rays from BHCs in the X-ray low (hard) state, with the occasional appearance of peaked noise or quasi-periodic oscillations (QPO). The rms variability is typically of order tens of percent of the average intensity. For recent reviews, see van der Klis (1994 & 1995). The GRO instruments find similarly strong, rapid variability in gamma-ray emission from sources in the X-ray low (hard) state; see e.g. van der Hooft et al. (1996) for GRS 1716–249 and Grove et al. (1994) for GRO J0422+32.

Recent results from RXTE indicate that the superluminal sources GRO J1655–40 and GRS 1915+105 in the X-ray high (soft) state both show weaker rapid X-ray variability (of order several percent rms) and QPOs on many timescales, at frequencies up to 67 Hz in the latter case (Morgan, Remillard, & Greiner 1997), while such variability is undetected in the gamma-ray band, where the statistical limits are $\sim 5\%$ (Crary et al. 1996, Kroeger et al. 1996).

Using the BATSE instrument, van der Hooft et al. (1996) studied the evolution of the rapid time variability of GRS 1716–249 (GRO J1719-24) throughout an entire ~ 80-day outburst. The power density spectrum showed a strong QPO with a centroid frequency that increased from ~ 0.04 Hz at the onset of the outburst to ~ 0.3 Hz at the end. Interestingly, they reported that the power spectrum could be described with a single characteristic profile, the frequency scale of which stretched proportionally during the outburst, and that the total power, integrated over a scaled frequency interval, was constant

throughout the outburst.

The upper panel of Fig. 6, adapted from Grove et al. (1994), shows the normalized power density spectra (PDS) in the 35-60 keV and 75-175 keV bands for the OSSE observation of GRO J0422+32. The shape of the power spectrum is essentially identical in the two energy bands. It shows breaks at a few 10^{-2} Hz and a few Hz, and a strong peaked noise component at 0.23 Hz, with FWHM ~ 0.2 Hz. The peaked noise profile is broad and asymmetric, with a sharp low-frequency edge and a high-frequency tail; thus the physical process responsible for the peaked noise appears to have a well-defined maximum timescale. We note that, in contrast to GRS 1716–249, the characteristic frequencies of the shoulders and the peak are independent of source intensity. (In passing we also note the striking similarity of the power spectrum of GRO J0422+32 to that of the X-ray burster 1E1724–3045 derived from RXTE data, including both a low-frequency and a high-frequency break and a strong peaked noise component. See Olive et al. in these proceedings for details).

The lower panel shows the time lag spectrum between these two energy bands: the hard emission (75–175 keV) lags the soft emission (35–60 keV) at all Fourier frequencies, falling crudely as $1/f$, up to about 10 Hz, where there is no statistically significant lag or lead between the two bands. In the 10–30 Hz frequency range, time lags as small as 1 ms would be detectable at $>99\%$ confidence. At frequencies ~ 0.01 Hz, hard lags as large as 300 ms are observed. There is no significant change in the lag at the frequencies dominated by the strong peaked noise component at 0.23 Hz.

The lag of GRO J0422+32 as a function of Fourier frequency is quite similar to the lags reported from Cyg X-1 (Miyamoto et al. 1988; Cui et al. 1997; Wilms et al. 1997), N Mus 1991 and GX339–4 (Miyamoto et al. 1993), in rather different energy ranges. The OSSE data from GRO J0422+32 provide more evidence indicating that the frequency-dependent time lag is a common phenomenon shared by many, if not all, accreting objects in binaries.

This form of PDS and the $1/f$ dependence of time lag on the Fourier frequency, first observed in Cyg X-1 by Ginga (Miyamoto et al. 1988), are very different from that expected in accretion models which presumably produce most of the X-ray and γ-ray emission from a region whose size is comparable to that of the last stable orbit around a black hole of mass a few M$_\odot$: The characteristic time scale associated with the dynamics of accretion in such an object is of order 10^{-3} sec, and consequently one would expect most of the associated power in the kHz frequency range. By contrast there is a remarkable *lack* of power at this range.

The shape of the PDS of accreting BHC has been the source of much discussion, but there exists no widely accepted, compelling theory which provides a "reasonable" account of it. While most of the attention to date has been focused on the $1/f$-like noise in the intermediate frequency regime ($\sim 0.01 - 10$ Hz), the breaks at both the low and high frequencies deserve equal atten-
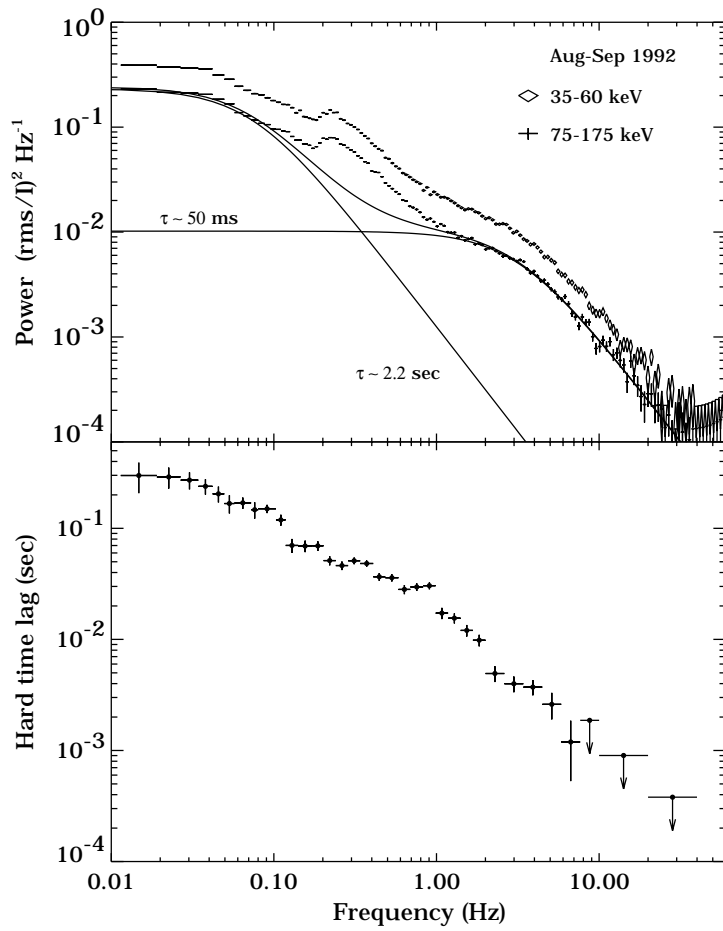
FIGURE 6. Upper panel: OSSE power density spectra of GRO J0422+32 in ∼35–60 keV and 75–175 keV energy bands. From Grove et al. (1994). Lower panel: Time lag spectrum between same energy bands.

tion. It is puzzling both that there is a lack of high-frequency power and that most of the variability power appears concentrated at the low frequency break, i.e. 4–5 orders of magnitude lower than the frequencies associated with the dynamics involved with the production of X-rays.

Generally, the models of BHC variability attempt to reproduce the observed shapes of the PDS (in fact, mainly the slope of their power-law section) as an ensemble of *exponential* shots with a range of decay times and/or amplitudes. The ensemble of shots is usually derived by simulating the accretion onto the BH in terms of avalanche-type models with Self Organized Criticality (Bak 1988; Negoro et al 1995).

This approach gives very little physical insight into the breaks at low and high frequencies, and it may well be erroneous at the outset. The reason is shown in Fig. 6b, the time-lag spectrum. The roughly-$1/f$ dependence of time lag on the Fourier frequency is very different from that expected if the 35–175 keV radiation results from Comptonization of soft photons by hot electrons in the vicinity of a black hole; under these conditions the time lags, which are indicative of the photon scattering time in the hot electron cloud, should be independent of the Fourier frequency and of order 10^{-3} sec, the photon scattering time in this region, which is roughly similar to the dynamical time scale.

The observed lags (Fig. 6b) are generally much longer and Fourier-frequency dependent, a fact noticed first by Miyamoto et al. (1988). The very long observed lags ($\simeq 0.3$ sec) and in particular their dependence on the Fourier frequency exclude from the outset models in which the variability is produced by mechanisms which effect a modulation of the accretion rate. These models, while they are constructed to produce the observed PDS, since they produce the hard radiation from Comptonization in vicinity of the black hole, would yield very short, frequency independent lags.

The discrepancy prompted Kazanas, Hua & Titarchuk (1997) to propose that the density of the hot electron cloud responsible for the formation of the high energy spectra, through the Comptonization process, is not uniform. Specifically they found that the $1/f$ dependence of the hard X-ray lags on Fourier frequency could be accounted for if the density profile of the hot scattering medium, $n(r)$, is of the form $n(r) \propto 1/r$ for radial distance r ranging from $\sim 10^6$ to 10^{10} cm. Because this model keeps Comptonization as the mechanism for the production of high energy photons, it can at the same time explain both energy spectra and the time variablity (Hua, Kazanas & Cui 1997). According to this interpretation, the aperiodic variability of these sources, to which little attention has been paid so far, can provide diagnostics to the density structure of the accreting gas around the black holes (Hua, Kazanas & Titarchuk 1997), an important information for understanding the accretion precess (e.g. Narayan & Yi 1994).

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