

## Timing Noise Properties of GRO J0422+32

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### ABSTRACT

OSSE observed the transient black hole candidate GRO J0422+32 (XN Per 92) between 1992 August 11 and 1992 September 17. High time resolution data were obtained in several energy bands over the  $\simeq 35\text{--}600$  keV range with a timing resolution of 8 ms. Power spectra at energies below 175 keV show substantial low-frequency red noise with a shoulder at a few  $10^{-2}$  Hz, peaked noise with characteristic frequency near 0.2 Hz, and a second shoulder at a few Hz. The frequencies of the shoulders and the peak are independent of energy and source intensity. The complex cross spectrum indicates that photons in the 75–175 keV band lag photons in the 35–60 keV band by a time roughly proportional to the inverse of the Fourier frequency. The maximum lag observed is  $\simeq 300$  ms. The power and lag spectra are consistent with the production of the  $\gamma$  rays through thermal Comptonization in an extended hot corona with a power-law density profile.

*Subject headings:* accretion, accretion disks — black hole physics — gamma rays: observation — stars: individual (GRO J0422+32)

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## 1. Introduction

The hard X-ray transient GRO J0422+32 (XN Per 1992) was discovered by the BATSE instrument on the Compton Gamma Ray Observatory in data from 1992 August 5 (Paciesas et al. 1992), and at its peak reached an intensity in soft  $\gamma$  rays approximately three times brighter than the Crab Nebula and pulsar. The source was observed by CGRO/OSSE beginning 1992 August 11, approximately at the peak of the outburst.

An optical counterpart was proposed by Castro-Tirado et al. (1992) and confirmed by the soft  $\gamma$ -ray observations of SIGMA (Roques et al. 1994). While the mass function of  $1.2 \pm 0.04 M_{\odot}$  determined by Filippenko, Matheson, & Ho (1995) is low enough that the compact object might indeed be a neutron star, the  $H\alpha$  radial velocity curve and the M stellar type of the mass donor imply a mass of  $3.6 M_{\odot}$  for the compact primary. The photometric measurements of Callanan et al. (1996) support this mass estimate and give a distance estimate of  $\sim 2$  kpc.

Broadband energy spectra from TTM, HEXE, and OSSE show that during outburst the source was in the X-ray low, hard state, which coincides with the breaking  $\gamma$ -ray state (Grove et al. 1997, 1998, and references therein). The gamma radiation is thus likely the result of thermal Comptonization in a hot corona near the accretion disk. The  $\gamma$ -ray spectrum hardened ( $\Delta kT/kT \simeq +20\%$ ) as the outburst declined (Grove et al. 1998).

Power spectra above 20 keV show significant red noise and peaked noise components frequently referred to as “quasi-periodic oscillations” (QPOs), even though they do not necessarily satisfy the width requirement ( $\text{FWHM}/f_0 < 0.5$ ) for such a label. BATSE reported “QPOs” centered at roughly 0.04 Hz and 0.2 Hz (Kouveliotou et al. 1992), both of which were confirmed by SIGMA (Vikhlinin et al. 1995) and OSSE (Grove et al. 1992, 1994).

The spectral shape, rapid variability, and outburst lightcurve are similar to previous X-ray novae A0620-00 and XN Mus 1991, both of which have measured mass functions that make them very strong black hole candidates (BHCs). Based on these similarities, GRO J0422+32 has been classified as a black hole candidate.

## 2. Observations

The OSSE instrument consists of four identical large-area NaI(Tl)–CsI(Na) phoswich detector systems (Johnson et al. 1993). Energy spectra and high time-resolution counting rates are accumulated in an alternating sequence of two-minute measurements of source and

background fields. High time-resolution data were collected from the on-source detectors in 8-ms rate samples in five energy bands from  $\simeq 35$  keV to  $\simeq 600$  keV.

OSSE observed GRO J0422+32 on 34 days spanning 1992 August 11 – 1992 September 17. The source reached its maximum intensity at 100 keV shortly after the start of the OSSE pointing, then began a roughly exponential decline with a decay time of  $\simeq 40$  days, falling to about half maximum intensity at 100 keV at the end of the pointing.

Some 10% of the total light yield of NaI(Tl) results from a phosphorescence with a decay time of  $\sim 150$  ms (McKlveen & McDowell 1975). Fluctuations in this “afterglow” from the passage of a heavy cosmic ray can trigger the OSSE detector system, evidenced as clusters of low-energy events with a soft spectrum ( $\sim E^{-5}$ , detectable up to  $\simeq 100$  keV) and in power spectra of blank sky pointings as weak broad-spectrum noise roughly consistent with exponential shots with time constant  $\simeq 70$  ms. We estimate that the residual noise power in the 35–60 keV band (normalized to the source intensity) after a screening process is applied to remove these events is  $< 10^{-3}$  (RMS/I) $^2$  Hz $^{-1}$  below 3 Hz and falls as  $1/f^2$  above 3 Hz (see Fig. 1 for comparison to the noise power from the source). The residual power is undetectable in the 75–175 keV band.

## 2.1. Power Spectrum Analysis

We obtained the power spectral density in the 35–60 keV and 75–175 keV energy bands through a multi-step process. We segmented the data into two-minute on-source pointings to reduce potential systematic effects that might arise on long timescales from orbital variations in the background count rate or differences between source-pointed detectors. To eliminate the possibility of spurious power spectral features (i.e. side-lobes) arising from the window function, we selected only those two-minute pointings that contained no data gaps or dropouts. Then we Fourier-transformed each 16384-point time series of 8-ms samples, normalized according to the procedure of Leahy et al. (1983), and subtracted the Poisson noise contribution, which we corrected for deadtime effects. We then summed the power spectra incoherently into daily and longer accumulations. Finally, following the prescription of Belloni and Hasinger (1990), we renormalized the power spectra to the source intensity, which we calculated from the background-subtracted spectral data from the standard OSSE analysis (Johnson et al. 1993). With this normalization, power spectra from different instruments, sources, and observations are directly comparable.

The normalized power spectral density (PSD)  $P_k$  at Fourier frequency bin  $k$  is given as

the fractional root-mean-square (RMS) variation of the source intensity  $I$ , viz.

$$P_k df = \frac{N_{tot}}{N_{src}^2} \left( \frac{2|H_k|^2}{n_{tot}} - p \right) \Delta f, \quad (1)$$

where  $N_{tot}$  is the total (i.e. source + background) counts in  $M$  Fourier transforms,  $N_{src}$  is the source counts—estimated from the standard spectral analysis—in these  $M$  transforms,  $|H_k|^2$  is the mean Fourier power at frequency  $k$ ,  $p \simeq 2$  is the Poisson noise power after accounting for deadtime effects,  $n_{tot} = N_{tot}/M$  is the mean of the total (i.e. source + background) counts per transform, and  $\Delta f = 1/131.072$  Hz is the frequency resolution of the power spectrum. We emphasize that this normalization is valid for the background-dominated case, which is appropriate for the low-energy gamma-ray band. The standard deviation of the PSD estimator is  $\sigma_k = P_k/\sqrt{M}$  (Bendat & Piersol 1986), which accounts for both intrinsic source noise and Poisson noise.

Figure 1a shows the normalized PSD in the 35–60 keV and 75–175 keV bands for the entire OSSE pointing. The total fractional RMS variation between 0.01 Hz and 60 Hz is  $\simeq 40\%$  in 35–60 keV, and  $\simeq 30\%$  in 75–175 keV. The shape of the power spectrum is essentially identical in the two energy bands. It shows breaks at a few times  $10^{-2}$  Hz and a few Hz, and a strong peaked-noise component (frequently labelled a “QPO”) at 0.23 Hz, with FWHM  $\simeq 0.2$  Hz. Statistically significant red noise is detected at frequencies up to  $\sim 20$  Hz. Not readily apparent in this figure is an intermittent peaked noise component at about 0.04 Hz. The amplitude of this feature varies from day to day. The two peaked-noise components and the lower-frequency spectral break have been reported elsewhere (Kouveliotou et al. 1992, Grove et al. 1992, Denis et al. 1994).

OSSE’s high sensitivity and high sampling rate have made the second spectral break apparent and permitted a study of the evolution of the various components that comprise the noise spectrum. We found (Grove et al. 1994) that the integrated 0.01–60 Hz power increased as the intensity of the source decreased, i.e. total power was anticorrelated with intensity and correlated with spectral hardness. In addition, while the intensity in these energy bands dropped by nearly a factor of two and the energy spectrum hardened by  $\sim 20\%$  in effective temperature over the course of the OSSE observation, the frequencies of the two breaks and the main peaked noise remained constant, i.e. there was no evidence for significant variability in the timescales of the noise processes.

## 2.2. Lag Spectrum Analysis

From the cross-spectral density (Bendat & Piersol 1986), one can measure the phase or time lag between two series as a function of Fourier frequency. Given two time series, e.g.

of soft photons  $s(t_k)$  and hard photons  $h(t_k)$ , the cross-spectral density  $C_{sh}(f_k)$  is given by

$$C_{sh}(f_k)df = \frac{2}{M} \sum S_m^*(f_k)H_m(f_k)\Delta f \quad (2)$$

where the sum runs over the  $M$  Fourier transforms  $S_m(f_k)$  and  $H_m(f_k)$  of the segmented soft and hard time series, respectively. The phase difference  $\Delta\phi_{sh}(f_k)$  at Fourier frequency  $f_k$  between the two series is then

$$\Delta\phi_{sh}(f_k) = \arctan\left(\frac{Im[C_{sh}(f_k)]}{Re[C_{sh}(f_k)]}\right) \quad (3)$$

where  $Im[C_{sh}(f_k)]$  and  $Re[C_{sh}(f_k)]$  are the imaginary and real parts, respectively, of the cross-spectral density. Time lags are simply computed from the phase lags by dividing by  $2\pi f_k$ . Following van der Klis et al. (1987), we correct for deadtime-induced cross-talk between the two bands by subtracting the mean cross-spectral density in the 40–62.5 Hz range from the entire cross spectrum. Because the imaginary part is negligible in this frequency range, the subtraction does not alter the sign of the phase differences at lower frequencies, and it has negligible effect on the amplitude of the phase differences at frequencies below  $\sim 10$ –20 Hz. We have used the standard deviation of the phase difference given by Bendat & Piersol (1986), which is strictly applicable only for noiseless measurements. Poisson noise causes this to be an underestimate above a few Hz (Vaughan & Nowak 1997), but this effect does not alter our conclusions.

The phase and time delay spectra we derive for the entire observation of GRO J0422+32 are shown in Fig. 2. The hard emission (75–175 keV) lags the soft emission (35–60 keV) at all Fourier frequencies, except above 10 Hz, where there is no statistically significant lag or lead between the two bands. The phase lag is a weak function of Fourier frequency and peaks near 1 Hz. The peak lies far below the Nyquist frequency and is therefore not a consequence of the finite data binning, as discussed by Crary et al. (1998). At frequencies  $\sim 0.01$  Hz, hard lags as large as 300 ms are observed, and the time lag falls roughly as  $1/f$ . There is no significant change in the lag at the frequencies dominated by the strong peaked noise component at 0.23 Hz.

### 3. Discussion

Generally similar power spectra have been reported from a number of black hole candidates, and beginning with Terrel (1972), they have frequently been modeled as arising from a superposition of randomly occurring bursts, or “shots”. If the shots have an instantaneous rise and exponential decay (or vice versa) with time constant  $\tau$ , the

resulting power spectrum is constant below the characteristic frequency  $1/(2\pi\tau)$  and falls as  $1/f^2$  at high frequencies. This type of model can describe the two breaks and the  $1/f^2$  behavior above several Hz in the power spectrum of GRO J0422+32 if there exist (at least) two independent shot components, with e-folding times  $\tau_s \simeq 50$  ms and  $\tau_l \simeq 2.1$  sec. The PSD of the two-shot model is shown for the 75–175 keV band in Fig. 1a. Note that the best-fit values of the long and short e-folding times and the ratio of amplitudes of the two components are independent of energy (Table 1).

Subtracting the PSD of the two-shot model from the observed PSD gives a peaked noise profile that is broad and asymmetric, with a sharp low-frequency edge and a broad high-frequency tail, as shown in Fig. 1b. Plausible alternative descriptions of the continuum between 0.1 and 1.0 Hz, e.g. a simple power law with index  $-0.9$ , do not significantly alter the shape of the peaked noise, although they may change its amplitude. The sharp low-frequency edge indicates that the physical process responsible for the peaked noise has a well-defined maximum timescale. This process may perhaps be thermal-viscous instabilities in the accretion disk (Chen & Taam 1994) or oscillations in a Comptonizing corona (Cui et al. 1997).

We attempted to fit the total PSD with simple analytic forms—e.g. in the time domain, multiple exponentially-damped sinusoids; or in the frequency domain, multiple zero-centered Lorentzians to model the continuum and offset Lorentzians to model the peaked noise—but none of these adequately describes the sharp rise and broad fall of the peaked noise, nor do they add significantly to our understanding of the characteristic timescales represented in the PSD. Similarly, the scenario of Vikhlinin, Churazov, & Gilfanov (1994), in which shots arise from a common reservoir and are coupled through a weak amplitude or probability interaction that generates QPOs, also fails to describe the observed PSD in detail.

The lag spectrum (Fig. 2) is generally similar to that of several other BHCs in the Ginga or Rossi XTE/PCA band (i.e. below 40 keV). In the X-ray low, hard state, these include Cyg X-1, GX339-4, and GS2023+338 (Miyamoto et al. 1992), and 1E1740.7-2942 and GRS 1758-258 (Smith et al. 1997). In the X-ray very high state, BHCs with similar lag spectra are GS1124-683 and GX339-4, subtype “C+D” for the latter object (Miyamoto et al. 1993). Furthermore, the lag spectrum is quite similar to that between 20-50 keV and 50-100 keV from Cyg X-1, which appeared to be essentially independent of the X-ray or  $\gamma$ -ray state (Crary et al. 1998). The present result is more evidence indicating that the frequency-dependent time lag is a common phenomenon shared by many accreting objects in binaries.

The observed power and lag spectra are at odds with the predictions of accretion models that produce most of the X-ray and  $\gamma$ -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; hence 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. Furthermore, under these conditions the time lags, which in these models are indicative of the photon scattering time in the hot electron cloud, should be independent of the Fourier frequency and also of order  $10^{-3}$  sec, the photon scattering time in this region.

Miller (1995) has argued that the observed time lags represent lags intrinsic to the soft seed photons, rather than the Comptonizing cloud. However, Nowak & Vaughan (1996) have shown that any intrinsic lag is washed out if the observed photon energies are much greater than the seed photon energies, as is the case here, leaving again a frequency-independent lag due to the difference in scattering times across the cloud.

The discrepancy between observed and predicted power and lag spectra prompted an alternative approach proposed recently by Kazanas, Hua & Titarchuk (1997; hereafter KHT) and Hua, Kazanas & Titarchuk (1997). These authors suggested that, while the process responsible for the formation of the high energy spectra is indeed Comptonization, the hot, scattering electron cloud extends over several decades in radius with a power law profile in density,  $n(r) \propto 1/r^p$ . This power-law density profile has a number of properties of interest in interpreting timing and spectral observations.

For a  $\delta$ -function injection of soft photons at the center of the cloud, the light curves of the photons emerging from the cloud at a given energy are power laws extending in time to  $\sim r/c$  ( $r$  is the outer edge radius of the atmosphere) followed by an exponential cutoff. For small values of the total Thomson depth  $\tau_0$ , the power-law index of the light curve is roughly equal to the power-law index  $p$  of the density profile of the scattering cloud, becoming progressively flatter for increasing values of  $\tau_0$  and higher escaping energies (Fig. 1 in KHT). On the other hand, the corresponding light curves for clouds of uniform density are exponentials without power-law portions. The time dependence of the photon flux can therefore be used to map the radial density profile of the scattering cloud.

For a uniform cloud, the density profile has index  $p = 0$ , and the light curve has no power law portion, i.e. the resulting PSD is that corresponding to an exponential shot. For a density profile with index  $p = 1$  and total Thomson depths in the scattering atmosphere of a few, the PSD is  $\propto 1/f$  (KHT Fig. 1). One should note that this form of the PSD assumes infinitely sharp turn-on of the shots at  $t = 0$ . As Kazanas & Hua (1997) have shown, a finite turn-on time  $t_0$  will introduce an additional steepening of the PSD at frequencies  $\omega \sim 1/t_0$  extending over a decade in frequency, yielding PSDs in agreement with those of Fig. 1a. The great advantage of the present scheme is therefore the direct

physical association of features in the PSD with properties of the source. Modeling of the light curves of GRO J0422+32 with this type of shot indicates values for  $t_0 \approx 50$  msec.

The model presented in KHT provides constraints on the time lags that can be of great value in probing the structure of the scattering medium. In the process of Comptonization, photons of energy  $E_2$  lag in time behind photons of energy  $E_1 < E_2$  simply because more scatterings are required to take a photon from  $E_1$  to  $E_2$ . The lag in time is proportional to the scattering time, which depends only on the density of the medium. Thus in general, for a uniform medium the lag time is constant (i.e. independent of the Fourier period). However, in a medium with a power-law density profile, the hard photons sample a range of several orders of magnitude in density, which appears in the corresponding time lags. In addition, because the probability of scattering at a given density range is constant for a medium with  $p = 1$ , all lags should be present with equal weight, producing a time-lag function  $\propto 1/f$ , with a maximum lag at the time scale corresponding to the scattering time at the edge of the power-law atmosphere. Indeed, Fig. 2 is in excellent agreement with the above arguments (see Hua, Kazanas, & Cui 1997a for fits to similar lag spectra from Cyg X-1, and Hua, Kazanas, & Cui 1997b for discussion regarding preliminary OSSE data from GRO J0422+32).

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Parameter	35-60 keV	75-175 keV
$\tau_l$	$2.1 \pm 0.1$ s	$2.1 \pm 0.1$ s
$\tau_s$	$53 \pm 3$ ms	$51 \pm 2$ ms
$A_l/A_s$ <sup>a</sup>	$2.0 \pm 0.2$	$1.9 \pm 0.1$

Table 1: Exponential shot fits to power spectra.

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<sup>a</sup>Ratio of amplitude of long to short decay-time shot components.

Fig. 1.— (a) Normalized power spectra for GRO J0422+32 in 35–60 keV (upper curve, diamonds) and 75–175 keV (lower curve, crosses) bands. Model fit (solid lines) to the 75–175 keV band includes exponential shots with lifetimes  $\simeq 50$  ms and  $\simeq 2.1$  sec. (b) Residual power after two-shot model is subtracted. Peaked noise components are visible near 0.04 Hz and 0.23 Hz. For clarity, only the 75–175 keV band is shown.

Fig. 2.— (a) Phase and (b) time lag of the hard emission (75–175 keV) relative to the soft (35–60 keV) emission from GRO J0422+32 as a function of Fourier frequency.



