OSSE SPECTRAL OBSERVATIONS OF GX 339-4 AND CYG X-1

D.A. Grabelsky, S.M. Matz, W.R. Purcell, and M.P. Ulmer
Northwestern University, Evanston, IL 60208

W.N. Johnson, R.L. Kinzer, R.A. Kroeger, J.D. Kurfess, M.S. Strickman,
J.E. Grove[1], R.A. Cameron[2], and G.V. Jung[2]
Naval Research Lab, Washington, DC 20375

M.D. Leising
Clemson University, Clemson SC 29634

ABSTRACT

The Oriented Scintillation Spectrometer Experiment on the *Compton Gamma Ray Observatory* has carried out spectral and timing observations of Galactic black-hole candidates GX 339-4 and Cyg X-1. GX 339-4 was observed as a target of opportunity in 1991 September, in response to the outburst reported by BATSE and SIGMA. The source was detected from 50 to 400 keV, at a level relative to the Crab of ~30%. During a follow-up observation made in 1991 November, the intensity of the source below 100 keV had dropped by nearly two orders of magnitude, and it was no longer detected above 100 keV. The observations of Cyg X-1 were made during three different observing periods between 1991 June and November. The OSSE time-averaged spectrum of Cyg X-1 is about 10 times brighter than that of GX 339-4, but remarkably similar in shape over the energy range in which both are detected. No significant emission is seen above about 1 MeV, and there is no evidence for any bumps or narrow lines near 0.511 MeV. The spectra of both sources are decribed reasonably well by a Comptonization model.

INTRODUCTION

The Galactic X-ray sources GX 339-4 and Cyg X-1 have long been considered prime black-hole candidates (Nolan *et al.* 1982; Liang and Nolan 1984; Makishima *et al.* 1986; and references therein). One of the observational properties of suspected black holes is an extremely hard spectrum, out to several hundred keV. While a hard spectrum does not by itself confirm the black-hole hyphothesis, high-quality spectral measurements are nevertheless important to the characterization of such objects.

The Oriented Scintillation Spectrometer Experiment on the *Compton Gamma Ray Observatory* observed both of these interesting sources during several *CGRO* viewing

[1]NRC/NRL Resident Research Associate
[2]Universities Space Research Association, Washington, DC

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periods in 1991. GX 339-4 was observed as a target of opportunity, in response to the 1991 August outburst reported by BATSE and SIGMA (*IAU Circulars* 5327, 5342, and 5352). Observations of Cyg X-1 were carried out as part of the OSSE viewing plan. This paper describes the observations, and discusses briefly some of the initial results.

OBSERVATIONS

OSSE observations of GX 339-4 were carried out during 1991 September 5 – 12 (viewing period 9), and 1991 November 7 – 14 (viewing period 13). In both viewing periods, the observations during the unocculted portion of each orbit were split evenly between GX 339-4 and a Galactic plane pointing. Each of the four detectors independently accumulated source and background spectra, chopping every 2 minutes. Background pointings were made at Galactic latitudes +4.5 and -8.5 degrees. The total on-source observing time (per detector) during the two viewing periods was 6.5×10^4 *sec* and 5.2×10^4 *sec*, respectively. In addition to the 2-minute spectra, count-rate timing data with 8-*msec* resolution were collected, covering an energy range of 50 – 200 keV.

During the first observation of GX 339-4, made soon after the peak of the outburst reported by BATSE, the source was detected from 50 to 400 keV at a level of roughly 30% of the Crab. The count-flux at 100 keV was $\sim 1.2 \times 10^{-4}\ cm^{-2}\ s^{-1}\ keV^{-1}$. No day-to-day variations in intensity or spectral shape were evident, although a ratio of the 80 – 200 keV to 200 – 400 keV energy bands shows a slight hint of softening over the course of the week. By the time of the second observation, GX 339-4 was no longer detectable above 100 keV, and its intensity below 100 keV had dropped by nearly two orders of magnitude.

Cyg X-1 was observed during three separate view periods: 1991 May 30 – June 15 (viewing period 2); 1991 August 9 – 15 (viewing period 7); and 1991 December 5 – 11 (viewing period 15). The instrument configuration during these observations included various combinations of detector coverage, as well as differing gain adjustments and offset pointing angles. The total on-source observation time ranged from 4.5×10^4 *sec* to 1.2×10^5 *sec*, per detector. During the first observation, count-rate timing data with 4 *msec* resolution were collected. During each viewing period, Cyg X-1 was observed at a count-flux of $\sim 7 \times 10^{-4}\ cm^{-2}\ s^{-1}\ keV^{-1}$ at 100 keV; the emission is detectable out to approximately 1 MeV. No spectral features are observed near 511 keV. The data do suggest variability on all timescales so far examined.

ANALYSIS AND RESULTS

Time-averaged count spectra for both sources were obtained by subtracting an estimated background spectrum from each 2-minute source spectrum, then summing the resulting background-subtracted spectra, detector-by-detector. The background for each 2-minute source spectrum was estimated from a quadratic fit to the three (or four) temporally nearest offset-pointed observations. Spectra averaged over intervals as short as 1 day, to as long as entire viewing periods, were produced in this way. Spectral fits were performed using a *forward-folding* technique, in which a model photon spectrum was convolved with the OSSE instrument response, resulting in a model count spectrum. The parameters of the model photon spectrum were adjusted so as to achieve a (least-squares) best fit of the model count spectrum to the measured count spectrum. Model photon spectra obtained by this fitting procedure are useful in evaluating specific source models, but cannot be used to fit other source models; the forward-folding procedure must be applied separately to each prospective model.

Spectra from each viewing period of Cyg X-1 and from the bright state of GX 339-4 were fitted with the Comptonization model of Sunyaev and Titarchuk (1980). For certain simplifying assumptions, this model predicts the gamma-ray spectrum that emerges from a spherical, hot plasma cloud, due to multiple Compton scatterings of soft ($\sim$ a few keV) photons injected in the central region of the cloud. The model is parameterized by the temperature of the cloud, kT, and by the cloud's optical depth, τ. Although the model does not provide a complete and detailed description of the source, it does appear to indicate that the spectra we observed are consistent with Comptonization.

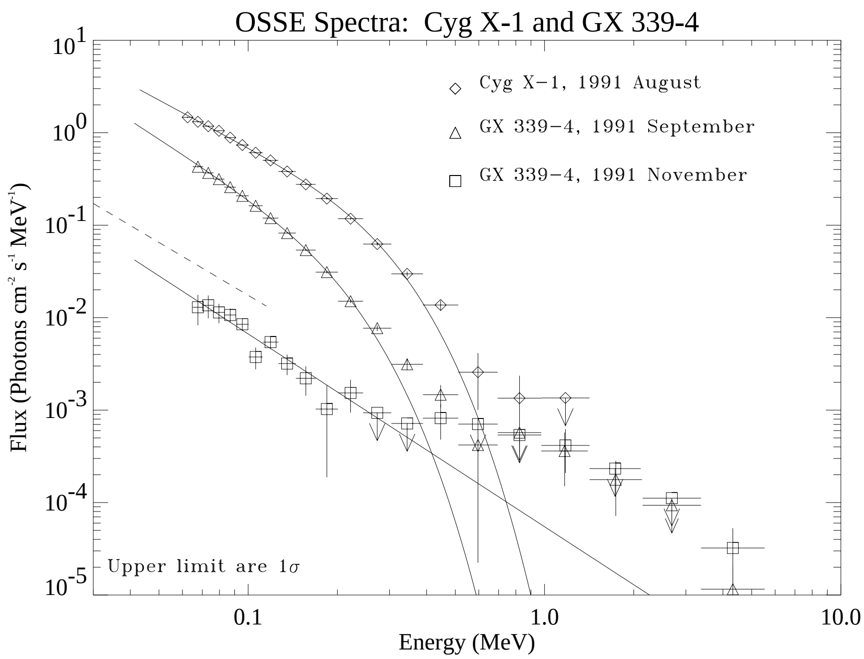

Figure 1: OSSE spectra of GX 339-4 and Cyg X-1. The Cyg X-1 (1991 August) and bright GX 339-4 spectra were fitted with the Comptonization model of Sunyaev and Titarchuk (1980); the dim GX 339-4 spectrum was fitted with a single power-law model. The solid lines show the best-fit model photon spectrum; the data points represent the *model-dependent* deconvolved count spectra (see text). The symbols for the three obserations shown are given in the figure legend. The dashed line shows the extrapolation of the power-law portion of the soft X-ray spectrum of GX 339-4 observed by Makishima *et al.* (1986).

The results of the fits are displayed in Figure 1, where the solid lines show the model photon spectra; for Cyg X-1, only the 1991 August observation is shown. The data points shown for each fit represent the "unfolded" count spectrum, determined by multiplying the measured count spectrum by the ratio of the best-fit model photon spectrum to the best-fit model count spectrum (the unfolded spectrum is also binned

Table 1: Comptonization Model Parameters

Observation	kT (keV)	τ	χ^2_ν	γ	$-\alpha$
Cyg X-1, 1991 May	60.06 ± 0.12	2.26 ± 0.05	10.8	3.27	-1.85
Cyg X-1, 1991 Aug.	59.05 ± 0.12	2.42 ± 0.06	1.16	2.99	-1.79
Cyg X-1, 1991 Dec.	52.16 ± 0.14	2.72 ± 0.09	18.6	2.81	-1.75
GX 339-4, 1991 Sept.	42.22 ± 0.11	2.39 ± 0.09	1.11	4.26	-2.05

in energy to improve the signal-to-noise). Figure 1 also shows the results of a power-law model for the 1991 November observation of GX 339-4.

It appears that the Comptonization model provides a fairly good description of the spectra of Cyg X-1 and GX 339-4 during its gamma-ray bright state, at least out to about 400 keV. Beyond this energy, the spectra seem to be harder than the model would predict. At these energies the spectra are beginning to trace the OSSE sensitivity curve (c.f., Cameron *et al.*, 1992), so the signal-to-noise is dropping off fairly quickly. But the discrepancy is undoubtedly also due in part to the inadequacy of the model and its assumptions, including the use of the classical Thomson scattering cross section and a single temperature for the entire plasma cloud.

With the understanding that the results are perhaps more qualitative than quantitative, we list the best-fit parameters (and reduced χ^2s) in Table 1, along with the derived quantities, γ and α. These are defined as:

$$\gamma = \frac{\pi^2}{3}\frac{mc^2}{(\tau + \frac{2}{3})^2 kT}$$

and

$$\alpha = -\frac{1}{2} + \sqrt{\frac{9}{4} + \gamma}.$$

γ gives the inverse of the average fractional energy gain of an emerging photon for the assumed geometry (i.e., the inverse of the Compton "y" parameter), and $-\alpha$ is the *photon* power-law index which describes the spectrum at energies below kT of the scattering medium. As a caution that these results are less than decisive, we note that a simple thermal bremsstrahlung model with kT = 71.1 keV fits the bright spectrum of GX 339-4 nearly as well as the Comptonization model.

The spectrum of GX 339-4 from the second (November) observation was fitted with a simple power-law photon model, because up to about 100 keV, where it "disappears" beneath the OSSE sensitivity curve, the spectrum clearly shows no signs of an exponential cutoff (Figure 1). The best-fit spectrum gives a photon index of $-\alpha = -2.09 \pm 0.20$, with a reduced χ^2 of 1.04.

DISCUSSION

GX 339-4 obviously underwent a transition during the time between the two OSSE viewing periods when it was observed, and, as noted above, may even have been softening during the first viewing. High and low X-ray states, previously observed, are anticorrelated with the intensity of a hard tail, which is well-described by a power law with a photon index of approximately -2 (e.g., Nolan *et al.* 1982; Makishima *et al.* 1986). This agrees with the index derived from the power-law fit to the second (dim) OSSE observation, as well as that for the extension of the Comptonization model to energies below kT. But it is not at all certain that the power law inferred from OSSE measurement is the continuation of the hard tail seen by lower energy experiments. As an example, the extrapolation of the high X-ray state observed by Makishima *et al.*, shown in Figure 1, is seen to lie between the two gamma-ray states observed by OSSE. Similarly, the slopes of the power-law extension of the Cyg X-1 spectra are in fair agreement with the results of lower energy observations.

The relatively good fits of the Sunyaev-Titarchuk model to the OSSE spectra of GX 339-4 and Cyg X-1 suggest that the spectra are shaped by Comptonization, despite the deficiency of the fits toward higher energies. By adding a second component to the model, with a distinct temperature and optical depth, a slight improvement to the fit can be obtained. A more realistic approach, however, probably requires proper treatment of the scattering cross sections, allowance for a temperature gradient in the scattering medium, and perhaps an alternative spatial distribution of the input soft photons. Time variability studies of the fluxes in these sources currently underway, including searches for QPO and cross correlation of different energy bands, may help provide further insights into the nature of GX 339-4 and Cyg X-1.

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