A&A manuscript no.
(will be inserted by hand later)

Your thesaurus codes are:
06(02.02.1; 08.09.2 Cyg X-1; 13.07.2)

ASTRONOMY
AND
ASTROPHYSICS
2.4.1996

Gamma Ray Observations of Cygnus X-1 with OSSE

B.F. Phlips[1], G.V. Jung[1], M.D. Leising[2], J.E. Grove[3], W.N. Johnson[3], R.L. Kinzer[3], R.A. Kroeger[3], J.D. Kurfess[3], M.S. Strickman[3], D.A. Grabelsky[4], S.M. Matz[4], W.R. Purcell[4], M.P. Ulmer[4], and K. McNaron-Brown[5]

[1] Universities Space Research Association, Washington DC
[2] Clemson University, Clemson, SC
[3] Naval Research Laboratory, Code 7650, Washington DC
[4] Department of Physics and Astronomy, Northwestern University, Evanston IL
[5] George Mason University, Fairfax, VA

Received ; accepted

Abstract. We report on $\sim$ 120 days of observations of Cygnus X-1 with OSSE onboard the Compton Observatory. Emission is detected in the range 50 keV to 1 MeV, and we find evidence for a continuum of hard X-ray spectra over a broad range of fluxes rather than the existence of distinct flux states. Comparisons of the source spectra with various theoretical models show that an exponentially truncated power law best describes the average spectrum in the OSSE energy band. Although we have measured a new minimum in the hard X-ray flux from the source, no evidence was found for either a broad 1 MeV feature or a narrow 511 keV line previously reported in association with a low flux state. Upper limits on such emission features are an order of magnitude lower than earlier reported detections. The 5.6-day periodicity of the source measured at optical wavelengths was not detected with a sensitivity to the rms modulation fraction of 5% in the 60-140 keV energy band.

Key words: Gamma Rays:Observations– Stars: Individual: Cyg X-1 – Black hole physics

1. Introduction

Cyg X-1, one of the brightest and most extensively studied gamma ray sources in the sky, is a 5.6-day binary system consisting of a blue supergiant (HDE 226868) and a compact companion of mass $\sim$6.3 $M_{\odot}$ (Gies et al. 1986, Dolan et al. 1989). Since the compact object has a mass greater than 3 $M_{\odot}$, Cyg X-1 is generally considered to be a prime black hole candidate, and it has become the prototype for back hole characterization and modeling. The possible presence of features in the spectrum of Cyg X-1 has been suggested as a useful criterion for distinguishing black hole systems from those containing neutron stars (Liang et al. 1992). In particular, features such as soft X-ray excesses or gamma-ray bumps in the hard X-ray/gamma-ray energy band have been proposed as signatures of black holes, giving special importance to an improved knowledge of the detailed shape of the Cyg X-1 spectrum at high energies.

The high-energy radiation from Cygnus X-1 is thought to be emission from an accretion disk surrounding a black hole (Shapiro, Lightman & Eardly 1976). The soft 1-10 keV X-ray spectrum has traditionally been described by a dominant low state with occasional periods of high state emission (e.g., Priedhorsky et al. 1983). The hard X-ray flux is well represented by a thermal Comptonization spectrum (Sunyaev and Titarchuk 1980). Using HEAO-3 data, Ling et al. (1987) identified three distinct levels for the 45-140 keV flux occuring during the low X-ray state, which they labeled $\gamma1$, $\gamma2$ and $\gamma3$, with $\gamma1$ being the state with the lowest 45-140 keV flux.A gamma-ray excess, characterized by a 1.2 MeV wide gaussian at 1 MeV with a line flux of 1.6 x 10^{-2} ph cm^{-2} s^{-1}, was detected in fall 1979 when Cyg X-1 was in the $\gamma1$ state (Ling et al. 1987). A weak 2σ detection of a narrow 511 peak was later reported from analysis of the HEAO data during the same episode (Ling et al. 1989). Other groups have also reported measurements of MeV emission from Cyg X-1 (see Owens and McConnell 1992 for a review of the MeV observations). Recently, Harris et al. (1993) derived upper limits for flaring episodes of 12 or more days from the long-term data base of the gamma ray spectrometer on SMM, and McConnell et al. (1994) reported no evidence for MeV features from the Cyg X-1 in data from COMPTEL.

In this paper, we present results of measurements of Cyg X-1 using OSSE. Given the importance of testing the models of the source and resolving the conflicting na-

Send offprint requests to: B. Phlips

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **1996**	2. REPORT TYPE	3. DATES COVERED **00-00-1996 to 00-00-1996**

4. TITLE AND SUBTITLE **Gamma Ray Observations of Cygnus X-1 with OSSE**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Research Laboratory,Code 7650,4555 Overlook Avenue, SW,Washington,DC,20375**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**		**4**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

ture of some of the previous measurements, OSSE devoted 122 days to observing the source at different intensity levels during the first four years of the CGRO mission. The shape of the spectrum, the search for narrow and broad spectral features, the light curve of daily flux averages, the flux levels of the source, and correlations of hardness ratios are addressed.

2. Observations

The OSSE experiment observed Cyg X-1 during 17 intervals, each spanning one or more days in the first four years of the CGRO mission, for a total of $\sim$2.4 x 10^6 live seconds of background-subtracted spectroscopy data. The observations were during the following CGRO viewing periods: 2, 7, 15, 203, 209, 212, 221, 223, 303, 318, 328, 331, 331.5, 332, 333, 419.5, 420. These data are not a random sample of the flux levels of the source because four of the observations, viewing periods 212, 221, 223 and 318, were in response to a low hard X-ray state detected by the Burst and Transient Source Experiment (BATSE). We performed a standard spectroscopic analysis of the data (Johnson et al. 1993) for each detector and each day separately, and the spectra were added at the end of the analysis. The timing analysis of these data at mHz to kHz frequencies is not considered here and will be presented elsewhere (see Bridgman et al. 1994 for an early analysis).

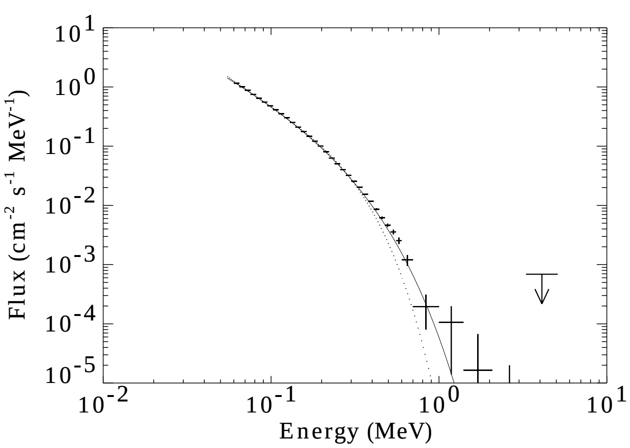

Fig. 1. Spectrum of the sum of all Cyg X-1 data with the best fit exponentially truncated power law (solid) and thermal Comptonization model (dotted).

3. Temporal Analysis

The integrated flux in the 45-140 keV band was monitored for each day of data and a continuum of intensities rather than obvious discrete states was detected. This becomes clearer when the daily flux is observed over a long period of time, as is done by BATSE (Paciesas et al. 1994). Compared with the historic γ1, γ2 and γ3 levels, the observations of February 1994 (CGRO viewing period 318) revealed a flux intensity of $\sim$ 1/5 the previously reported lowest flux in this band. The source has therefore a greater range of intensities than previously measured. Note, however, that no OSSE measurements have been performed at intensities comparable to the γ3 level.

The light curve shown can be searched for periodicities, in particular for the 5.6-day orbital periodicity. The data set is sparse, with only $\sim$100 days of data out of a 1024-day interval, with the contiguous daily data sets varying from two days to two weeks in length. We calculated the Fast Fourier Transform for the first 1024 days of the mission after we subtracted a fifth order polynomial in time to detrend the data.We find no evidence for periodicity in this sparse data set, other than a peak at very low frequency due to the data sampling. The upper limit to the amplitude of a 5.6-day periodicity is 0.005 γcm^{-2} s^{-1} in the 60-140 keV band, corresponding to an rms modulation fraction of $< 5\%$.

4. Spectral Analysis

The spectrum for the sum of all data through May 1995 is shown in Figure 1. The spectrum is smooth, without breaks or line features. It extends from 60 keV, the lower threshold used in this spectral analysis, to $\sim$1 MeV, where the flux level falls below the OSSE sensitivity. The high statistical precision of the Cyg X-1 spectrum permits differentiation among theoretical models to much higher energies than previously possible. We use the four different functional forms to fit the data: a two-parameter thermal bremsstrahlung model without Gaunt factor(flux at 100 keV, =0.476 γcm^{-2}s^{-1}MeV^{-1}, kT=108 keV), the three-parameter thermal Comptonization spectrum of Sunyaev and Titarchuk (1980)(flux at 100 keV= 0.465 γcm^{-2}s^{-1}MeV^{-1}, kT=65 keV, τ=1.94), a three-parameter exponentially truncated power law (flux at 100 keV= 0.470 γcm^{-2}s^{-1}MeV^{-1}, E_{cutoff}=158 keV, photon index=1.39), and we also include the possibility that some fraction of the emission described by an expentially truncated power law is incident on a cold optically thick scattering medium (flux at 100 keV= 0.473 ph cm^{-2}s^{-1}MeV^{-1}, E_{cutoff}=156 keV, photon index=0.96, reflection=1.5). The effects of Compton reflection are contained in a code provided by Zdziarski (1995) to perform the analysis. The model contains a reflection parameter that is proportional to the solid angle covered by the reflection medium. All fits were over the energy range from 60 keV to 4 MeV.

The model with an exponentially truncated power law gives the best fit to the data. The thermal bremsstrahlung and the thermal Comptonization models both diverge from the measured spectrum at higher energies where they underestimate the flux from the source. The exponentially truncated power law with reflection produces a slightly worse fit to the data, and the fit improves as the amount of reflection decreases. The difference in the photon spectra between the model with and without reflection occurs mostly at the lower end of the OSSE energy range, where the systematic errors in the instrument efficiency and calibration are largest. The confidence in rejecting models based solely on the lowest energy bins is therefore smaller than the confidence in rejecting models which diverge at higher energies. The exponentially-truncated power law is also the best model when each viewing period is summed and fitted separately. The optically thin thermal bremsstrahlung model still provides a good fit to the daily spectra. This simple two-parameter model is used to study the temperature-intensity dependence of the source. Figure 2 shows that the temperature of the source and the intensity vary within a limited range, except for a few excursions to the low temperature- low amplitude regime. During the very low flux observation of February 1994, the temperature of the source was $\sim$ 70 keV compared with 110 keV for the other observations. Note that the scatter in the points on this figure is much larger than the statistical or systematic errors. Alternatively fitting the daily data with the thermal Comptonization model derived by Sunyaev and Titarchuck (1980), we find a similar scatter in the optical depth parameter, with the temperature fairly constant with a mean of 65 keV and a standard deviation of less than 5 keV.

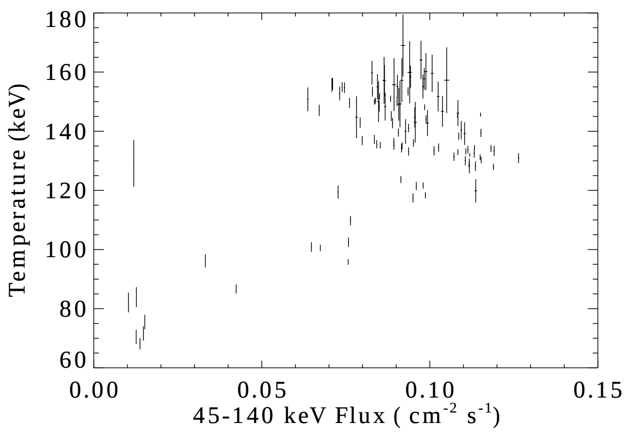

Fig. 2. Temperature versus 45-140 keV integrated flux, for each day, obtained using an optically thin bremsstrahlung model.

In Figure 3, we display spectra in terms of E^2Flux(E) in order to highlight the energy of peak power output in the OSSE band and emphasize the differences between spectra measured at different flux states. The spectrum with open squares is the sum of all days with a flux (in the 45-140 keV band) of less than 0.06 γcm^{-2} s^{-1}. The spectra with filled squares, open circles and filled circles are for a flux between 0.06 and 0.08, between 0.08 and 0.105 and greater than 0.105 γcm^{-2} s^{-1}, respectively. The low amplitude spectra are more like a power law than the other data.

5. Search for line features

To search for any spectral features associated with specific flux levels that would have been averaged out in the total spectrum, the data were divided into individual days and each day was analyzed separately. Following the analysis of Ling et al. (1987), we searched for the presence of MeV bumps by fitting each day of data with a thermal bremsstrahlung spectrum and a 1.2 MeV wide gaussian line feature centered at 1 MeV. We see no significant amplitude for a broad gaussian feature for any flux level of the source. When all the data are added together, as in Figure 1, the 90% confidence level (CL) upper limit to the 1 MeV line is 4 x 10^{-4} γcm^{-2} s^{-1}, compared to the flux of 1.6 x 10^{-2} γcm^{-2} s^{-1} measured by Ling et al. The 95% CL upper limit for a 1-1.5 MeV wide feature near 4 MeV is 2.0 x 10^{-5} γcm^{-2} s^{-1} . The search for lines can be repeated

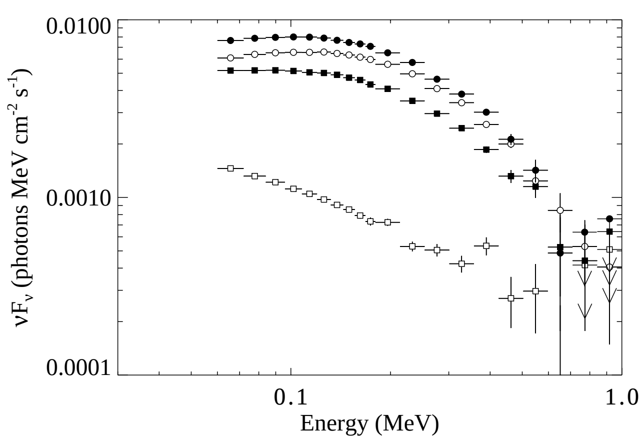

Fig. 3. Photon spectrum multiplied by the energy squared. The data were grouped into four bins according to their 45-140 keV flux.

at any energy and width. Given the previous reports of a narrow 511 keV line, we fit the data for a narrow (< instrument resolution) 511 keV line for each day of data. We do not find any days with a significant excess 511 keV emission nor a correlation between the 511 keV emission and the overall source strength. The 90% CL upper limits to the amplitude are between 0.5 and 1.0 x 10^{-3} γcm^{-2} s^{-1} for most days. The 90% CL upper limit for a narrow 511 keV in the total spectrum is 7 x 10^{-5} γcm^{-2} s^{-1}.

6. Discussion

The variability of Cyg X-1 at gamma ray energies, is a factor of ~15, much greater even than the factor of ~3 measured during the HEAO-3 mission. However, the variability does not seem to be between discrete states but rather among a continuous range of possible flux values. The optically thin thermal bremsstrahlung fits to the individual days of data show that the source usually fluctuates in a seemingly random fashion in a narrow range of intensity-temperature phase-space. This is unlike the behaviour observed in GRO J0422+32, where the temperature is monotonically increasing in time as the transient decreases in brightness (Kroeger et al., 1995). The spectrum is best described by a model with optically thin Comptonization. However, a preliminary analysis reveals that this model cannot be applied to contemporaneous GINGA (Ebisawa, 1994) and OSSE data. A more complex model using an exponentially truncated power law with an angle dependent reflection component appears to fit both sets of data simultaneously (Zdziarski, 1995). Extrapolating the exponentially truncated power-law model to lower energies, we find that the calculated flux in the 3-11 keV range for viewing period 318 is ~3 times larger than for a typical observation. This anticorrelation between the extrapolated low energy X-ray flux and the measured gamma ray flux is consistent with earlier obervations (Priedhorsky et al. 1983) and is not very model dependent. The crossover energy for the low intensity gamma ray spectra to become dominant is between 10-20 keV.

We have searched for the amplitude of a broad MeV bump and a narrow 511 keV line. The distribution of the daily amplitudes of 1 MeV peaks (figure 4) is gaussian, with a small non-zero mean, indicating the underlying thermal bremsstrahlung distribution underestimates the continuum flux at 1 MeV by ~5 x 10^{-4} ph cm^{-2} s^{-1}. There is no evidence for an excess of points at high flux values, and no single day with an amplitude near that measured by Ling et al. (1987) over a 12 day period. The 90% CL upper limit to the 1 MeV bump flux is in the 1-4 x 10^{-3} γcm^{-2} s^{-1} range for most days. If MeV bumps of the intensity reported by Ling do exist, they must be transient within the $\gamma 1$ state. Our nondetection of MeV features limits the duty cycle of such a process. For 1-day emission episodes, there is a 90% probability we would have detected a duty cycle greater than 2.3%, or more than 25 outbursts over the first three years of the mission. For 4-day episodes the duty cycle must be less than 4.5%, and for 14-day episodes, it must be less than 9%, which corresponds to ~6.5 outbursts over the mission so far. According to the models of Dermer et al. (1989) and the compilation of data by Bassani et al. (1989), there should be an anticorrelation between the hard X-ray flux and the gamma ray flux. We have binned our data in two bands, 0.06-0.4 MeV and 0.4-1.5 MeV for a direct comparison with Bassani et al. From the total data set, one would conclude that there is a correlation, not an anticorrelation, between the gamma ray flux and the hard X-ray flux, consistent with higher temperatures at higher flux.

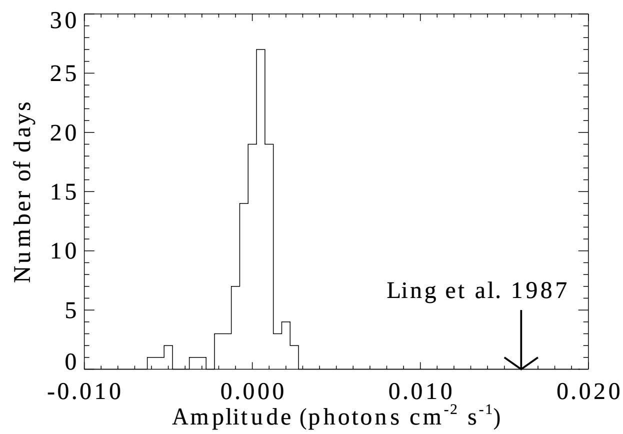

Fig. 4. Distribution of the daily amplitudes of the 1 MeV gaussians. The amplitude reported by Ling et al. (1987) is shown for comparison.

With the very low flux observations removed(45-140 keV flux < 0.08 ph $cm^{-2}s^{-1}$, see figure 2), the correlation coefficient of this ratio is 0.03, implying no correlation between the fluxes during most observations.

References

Bassani, L. et al. 1989, Astrophys. J., 343, 313
Bridgman, W.T. et al. 1994, Second Compton Symposium, AIP Conf. Proc 304, 225
Dermer, C.D., and Liang, E. P. 1989, AIP Conf. Proc. No. 170, ed. N. Gehrels(AIP, NY), 326
Dolan, J.F., and Tapias, S. 1989, Astrophys. J., 344, 830
Ebisawa, K. 1994, private communication
Gies, D.R., and Bolton, C. T. 1986, Astrophys. J.304, 371
Harris, M.J. et al. 1993, Astrophys. J., 416, 601
Johnson, W.N. et al. 1993, Astrophys. J. Supp., 86, 693
Kroeger, R.A. et al. 1995, submitted
Liang, E.P. et al. 1992, Compton Observatory Science Workshop, ed. C.R. Shrader, NASA Conf. Pub. 3137, 174
Ling, J.C., Mahoney, W. A., Wheaton, W. A., Jacobsen, A. S., and Kaluzienski, L. 1987, Astrophys. J., 321, L117
Ling, J.C., and Mahoney, W. A. 1989, Astrophys. J., 343, l57
McConnell, M.L. et al. 1994, Astrophys. J., 424, 933
Owens, A., and McConnell, M. L. 1992, Comments Astrophys., 16, 205
Paciesas, W.S. et al. 1994, Proc. NATO Advanced Study Institute Conf., Les Houches, ed. M. Signore (Kluwer, The Netherlands)
Priedhorsky,W.C.et al. 1983, Astrophys. J., 270, 233
Shapiro, S.L., Lightman, A.P., and Eardly, D.M. 1976, Astrophys. J., 204, 187
Sunyaev, R.A., and Titarchuk, L. G. 1980, A& A, 86, 121
Zdziarski, A.A. et al., 1994, MNRAS, 269, L55
Zdziarski, A.A., 1995, private communication

This article was processed by the author using Springer-Verlag LTEX A&A style file *L-AA* version 3.