

GAMMA-RAY OBSERVATIONS OF CYGNUS X-1 WITH THE ORIENTED SCINTILLATION SPECTROMETER EXPERIMENT

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ABSTRACT

We report on ~ 120 days of observations of Cygnus X-1 with OSSE on board the *Compton Gamma Ray Observatory*. Emission is detected in the range 50 keV–1 MeV, and we find evidence for a continuum of hard X-ray flux levels 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.

Subject headings: gamma rays: observations — stars: individual (Cygnus X-1) — stars: oscillations — X-rays: stars

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 black 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 Cyg X-1 is thought to be emission from an accretion disk surrounding a black hole (Shapiro, Lightman, & Eardley 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., Friedhorsky, Terrell, & Holt 1983). The hard X-ray flux is well represented by a thermal Comptonization spectrum (Sunyaev & Titarchuk 1980; Ling et al. 1983). Using *HEAO 3* data, Ling et al. (1987) identified three distinct levels for the 45–140 keV flux that occurred during the

low X-ray state, which they labeled γ_1 , γ_2 , and γ_3 , with γ_1 being the state with the lowest 45–140 keV flux. The intensity of the hard X-ray flux may be anticorrelated with the intensity of the soft X-ray flux (Bassani et al. 1989). A gamma-ray excess, characterized by a 1.2 MeV wide Gaussian at 1 MeV, with a line flux of 1.6×10^{-2} photons cm^{-2} , was detected in 1979 Fall, when Cyg X-1 was in the γ_1 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 & Wheaton 1989). Other groups have also reported measurements of MeV emission from Cyg X-1 (see Owens & McConnell 1992 for a review of the MeV observations, including calculations of equivalent line flux intensities). For example, Baker et al. (1973) described a spectral feature near 2 MeV, with positive emission up to 6 MeV. Mandrou et al. (1978) observed fluxes up to 3 MeV, although they did not see any bumps. McConnell et al. (1989) reported detecting a hard-spectral component out to 9 MeV. A general review of Cyg X-1 studies was written by Liang & Nolan (1984).

Although there is a wide spread of energies over which MeV emissions have been reported, these measurements suggest periods of spectral hardening in the MeV region beyond a simple extrapolation from the hard X-ray spectrum. There are, however, a considerable number of experiments (Schoenfelder et al. 1974; White et al. 1980; Nolan 1982; Varendorff et al. 1990) reporting featureless hard X-ray and gamma-ray spectra, and the limits derived from these experiments are well below the flux values measured by other experiments. In addition, Harris et al. (1993)

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derived upper limits for flaring episodes of 12 or more days from the long-term database of the gamma-ray spectrometer on the *Solar Maximum Mission* (SMM) and McConnell et al. (1994) recently reported no evidence for MeV features from Cyg X-1 in data from the COMPTEL experiment on the *Compton Gamma Ray Observatory* (CGRO).

The presence of enhanced emission near 1 MeV, such as that detected with *HEAO 3*, was interpreted by Liang & Dermer (1988) as the emergent radiation from a photon-starved, pair-dominated thermal plasma. In this picture, the hard X-rays are produced by thermal Comptonization of a copious soft photon source farther out in the disk, in accord with earlier models of the hard X-ray spectrum of Cyg X-1, and the innermost region, shielded from the soft photon flux, reached MeV temperatures. Spectral complexity is also found in the X-ray regime. Done et al. (1992) demonstrated the presence of a reflection component in *EXOSAT* and *HEAO 1* observations, and argued that a multitemperature thermal Comptonization model was required to give a good fit to the Cyg X-1 spectrum. Recently, Haardt et al. (1993) suggested that thermal Comptonization in an accretion disk corona is simply described by a power law with an exponential cutoff. Zdziarski et al. (1994) combined optically thin Comptonization and reflection into a model consisting of an exponentially cut off power law, with reflection in a form useful for data analysis. The excellent sensitivity of the OSSE measurements provides spectra with adequate precision to test these theoretical models.

In this paper, we present results of measurements of Cyg X-1 using the Oriented Scintillation Spectrometer Experiment (OSSE) on the *Compton Gamma Ray Observatory* (CGRO). Given the importance of testing the models of the source and resolving the conflicting nature of some of the previous measurements, OSSE devoted 122 days to observing the source at different intensity levels during the first 4 yr 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. We describe OSSE observations of Cyg X-1 in § 2, the temporal variability analysis in § 3, and spectral analysis in § 4. Our search for spectral features is presented in § 5, and discussion of the results is given in § 6.

2. OBSERVATIONS

The Oriented Scintillation Spectrometer Experiment is one of four instruments on the CGRO. The observatory was launched on board the space shuttle Atlantis on 1991 April 5, and has been operating in a 28° inclination low Earth orbit. OSSE consists of four identical and independently movable NaI-CsI phoswich detectors sensitive to gamma rays between 50 keV and 10 MeV. Each detector has a tungsten collimator that defines a 3.8×11.4 FWHM rectangular field of view, and active shielding provided by NaI anticoincidence detectors configured in an annulus around the main detector. Each detector has an effective area of ~ 500 cm² at 511 keV. Eight or 16 s spectra are accumulated on board and then transmitted to Earth for spectroscopic analysis, while limited event-by-event or fast-rate samples over certain energy bands are also accumulated in parallel for timing analysis. We will report here on analysis of the spectroscopy data. 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

TABLE 1
OSSE OBSERVATIONS OF CYG X-1

No.	Dates ^a	Viewing Period ^b	Total Live Seconds ^c × 10 ⁴
1.....	91/150-165	2	39.2
2.....	91/220-227	7.0	10.9
3.....	91/332-346	15	25.4
4.....	92/336-357	203	21.8
5.....	93/040-053	209	20.1
6.....	93/080-082	212	5.4
7.....	93/133-134	221	2.5
8.....	93/151-154	223	7.0
9.....	93/274-277	303.4	7.9
10.....	94/032-039	318.1	43.8
11.....	94/144-145	328	2.7
12.....	94/158-159	331	2.8
13.....	94/165-169	331.5	12.1
14.....	94/174-175	332	1.3
15.....	94/192-193	333	2.5
16.....	95/130-143	419.5	9.7
17.....	95/143-156	420	8.8

^a Dates are year/day of year.

^b CGRO mission timeline viewing period identification.

^c The total live time is the sum of the livetimes of the detectors observing the source.

analysis). Spectra are integrated into 2 minute intervals, alternately viewing the source field and background fields offset by $\sim 5^\circ$. Using the known response of the detectors, the background-subtracted count spectra are converted into photon spectra using a forward-folding technique. A full description of the instrument and standard methods of data analysis are given by Johnson et al. (1993).

OSSE observed Cyg X-1 during 17 intervals, each spanning 1 or more days in the first 4 yr of the CGRO mission, for a total of $\sim 2.4 \times 10^6$ live seconds of background-subtracted spectroscopy data. Table 1 summarizes these observations. The large spread in total live times of the different observations resulted from variations in the number of detectors used in the observation (1–4) and the length and quality of each observation. These data are not a random sample of the flux levels of the source because four of the observations, numbers 6, 7, 8, and 10, were in response to a low hard X-ray state detected by the Burst and Transient Source Experiment (BATSE) on CGRO (Fishman et al. 1989). The observations were analyzed for each detector and each day separately, and the spectra were added at the end of the analysis.

3. TEMPORAL ANALYSIS

The integrated flux in the 45–140 keV band for each day of data is shown in Figure 1, where the x -axis represents days of data with a short break between viewing periods that is not representative of the actual time between the observations. The energy band was chosen to match the band used in the analysis of the *HEAO 3* data. The data between 60 and 140 keV were fitted with a thermal bremsstrahlung spectrum, and the resulting fit was used to calculate a 45–140 keV flux. For the days when the instrument configuration provided spectra down to 40 keV, the calculated and measured flux were in agreement.

As seen in Figure 1, there are no obvious discrete states but rather a continuum of intensities. This becomes clearer when the daily flux is observed over a long period of time, as is done by the BATSE experiment (Paciesas et al. 1994).

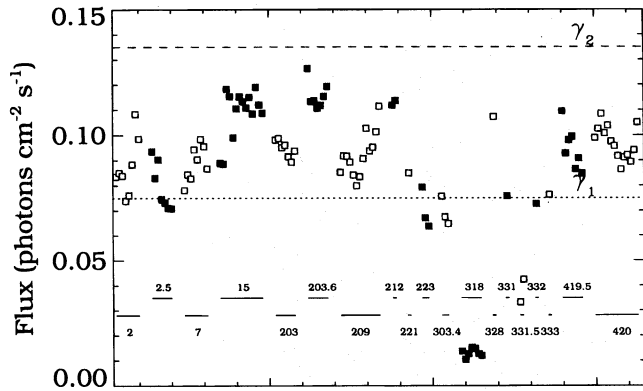


FIG. 1.—Flux in the 45–140 keV band for each day of Cyg X-1 data. Line segments show the viewing period associated with the data points. Also shown are the historic γ_1 and γ_2 states, as defined by Ling et al. (1987). Alternate viewing periods are shown with open and filled squares.

Compared with the historic γ_1 , γ_2 , and γ_3 levels, the observations of 1994 February (*CGRO* viewing period 318) revealed a flux intensity of $\sim \frac{1}{5}$ of 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 γ_3 level.

The light curve shown in Figure 1 can be searched for periodicities, in particular for the 5.6 day orbital periodicity. The data set is sparse, with only ~ 100 days of data out of a 1024 day interval, with the contiguous daily data sets varying from 2 days to 2 weeks in length. The measurements are therefore not very sensitive to periodicities between a few weeks and a few months. For this analysis the data were binned into individual days; therefore, the shortest detectable variability is 2 days. We calculated the fast Fourier transform of the mean subtracted data set for the first 1024 days of the mission and found most power at low frequencies because of overall trends in the data—more specifically, the significant drop in flux in 1994 February. To detrend the data, we subtracted a fifth-order polynomial in time and calculated the fast Fourier transform of the residuals. 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 5×10^{-3} photons $\text{cm}^{-2} \text{s}^{-1}$ in the 60–140 keV band, corresponding to an rms modulation fraction of less than 5%.

4. SPECTRAL ANALYSIS

The spectrum for the sum of all data through 1995 May is shown in Figure 2. The spectrum is smooth, without breaks

or line features. It extends from 60 keV, the lower threshold used in this spectral analysis, to ~ 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 four different functional forms to fit the data. The first is a simple two-parameter thermal bremsstrahlung model described by

$$\Phi(E) = KE^{-1}e^{-E/kT}, \quad (1)$$

where $\Phi(E)$ is the flux at energy E , K is the normalizing constant, and T is the temperature. The second functional form we use is the three-parameter thermal Comptonization spectrum of Sunyaev & Titarchuk (1980). It is derived for a spherical, uniform electron plasma with Thomson depth $\tau = n_e \sigma_T R$, where n_e is the electron density and R is the radius of the region, and is strictly valid in the nonrelativistic ($kT \ll m_e c^2$), diffusive ($\tau \gg 1$) regime. Higher temperature corrections have been derived by Titarchuk (1994) and Titarchuk & Hua (1995), but Monte Carlo simulations including pair production (Skibo et al. 1995) are required to provide accurate representations at all temperatures and optical depths. However, the Monte Carlo results and the refined model of Titarchuk (1994) agree closely with the original model of Sunyaev & Titarchuk (1980) for the parameter values of Cyg X-1.

The third functional form employed is a three-parameter exponentially truncated power law, given by

$$\Phi(E) = KE^{-\Gamma}e^{-E/E_c}, \quad (2)$$

where Γ is the photon spectral index and E_c is the cutoff energy. We also include the possibility that some fraction of the emission described by equation (2) is incident on a cold optically thick scattering medium for the fourth functional form we employ. The effects of Compton reflection are contained in a code provided by Zdziarski (1995). The model contains a reflection parameter that is proportional to the solid angle covered by the reflection medium: a reflection coefficient of 1 is a source just above an infinite plane of reflecting material; a coefficient of 2 implies that the source is embedded in the reflecting medium.

Table 2 lists the fits of these various models to the sum of all the Cyg X-1 data. The normalizing energy was fixed at 100 keV, and all daily fits were over the energy range from 60 keV to 4 MeV. When all the observations are added together, the systematic differences among detectors become important and the spectra have to be fitted detector by detector with the various models. The difference between the variance in the distribution of the parameters obtained and the square of the error in the fit parameters is used as a measure of systematic errors. The statistical errors are 68%

TABLE 2
FITS OF VARIOUS MODELS TO THE 122-DAY SUMMED CYG X-1 SPECTRUM

Model	Amplitude at 100 keV ($\gamma \text{ cm}^{-2} \text{ s}^{-1} \text{ MeV}^{-1}$)	kT, E_c^a (keV)	Photon Index	τ	χ^2/DOF
Thermal bremsstrahlung.....	$0.476 \pm 0.002(\pm 0.017)$	$108 \pm 1(\pm 5)$	...	...	50.0
Thermal Comptonization.....	$0.465 \pm 0.001(\pm 0.021)$	$65 \pm 1(\pm 3)$	...	$1.94 \pm 0.04(\pm 0.05)$	19.6
Power-law times exponential.....	$0.470 \pm 0.001(\pm 0.017)$	$158 \pm 3(\pm 12)$	$1.39 \pm 0.02(\pm 0.08)$	...	2.9
Power-law times exponential with reflection at 1.5.....	$0.473 \pm 0.001(\pm 0.017)$	$156 \pm 3(\pm 4)$	$0.96 \pm 0.04(\pm 0.08)$	...	8.3

^a For the thermal bremsstrahlung and Sunyaev-Titarchuk model, the parameter is kT . For the exponentially truncated power-law models, the parameter is the cutoff energy, E_c .

confidence intervals. The parameters in Table 2 are listed as the average of that parameter for all detectors, with the fit error followed by the systematic error, in parentheses. The reduced χ^2 quoted is the average χ^2 per degree of freedom of the fits over the detectors. The best-fit models given by the functional form of equation (2) and a thermal Comptonization model are overlaid on the data in Figure 2.

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 fit to the data slightly worse than without reflection, 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

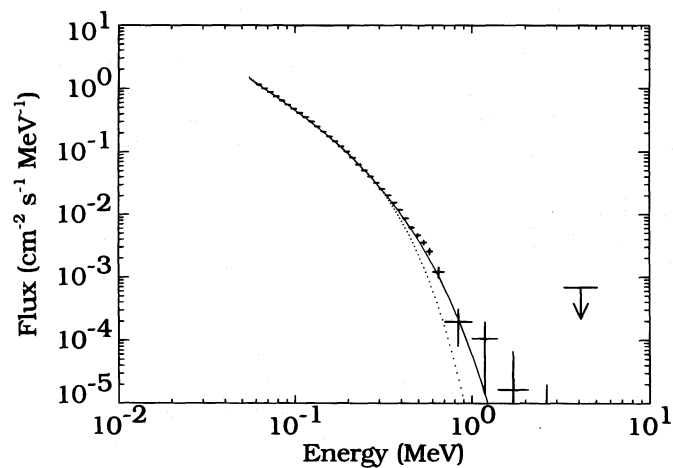


FIG. 2.—Spectrum of Cyg X-1 for all the data. Solid line is the best fit to the data with an exponentially truncated power-law model, while the dotted line is the best fit using the thermal Comptonization model of Sunyaev & Titarchuk (1980). Upper limits are 2σ . See Table 2 for the parameters of the fits.

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, like the thermal bremsstrahlung and thermal Comptonization models. The exponentially truncated power law is also the best model when each observation is summed and fitted separately. Table 3 lists the results of the fits to each observation, along with the source luminosity in the 60 keV–1 MeV range, assuming a Cyg X-1 distance of 2.5 kpc. The statistical error in the luminosity is 1% or better for all observations.

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 3 shows that the temperature of the source and the intensity vary within a limited range, except for a few excursions to the low-

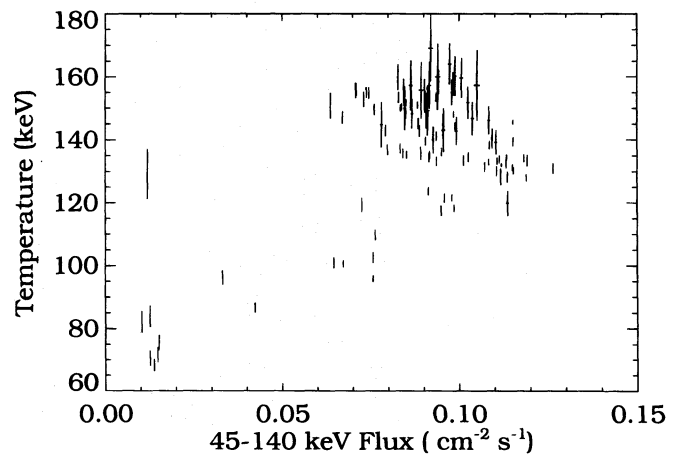


FIG. 3.—Temperature vs. 45–140 keV integrated flux for each day, obtained using an optically thin thermal bremsstrahlung model.

TABLE 3
FITS OF AN EXPONENTIALLY TRUNCATED POWER LAW TO THE
INDIVIDUAL CYG X-1 OBSERVATIONS

Observation Number	Amplitude at 100 keV ($\gamma \text{ cm}^{-2} \text{ s}^{-1} \text{ MeV}^{-1}$) $\times 10^{-3}$	E_c (keV)	Photon Index	Luminosity ^a (ergs s^{-1}) $\times 10^{37}$
1	624 ± 1	148 ± 2	-1.22 ± 0.01	1.30
2	657 ± 3	151 ± 9	-1.21 ± 0.05	1.39
3	826 ± 2	139 ± 3	-1.18 ± 0.02	1.68
4	752 ± 1	137 ± 2	-1.28 ± 0.02	1.46
5	644 ± 1	150 ± 3	-1.34 ± 0.02	1.28
6	777 ± 7	177 ± 25	-1.55 ± 0.01	1.54
7	613 ± 3	135 ± 6	-1.14 ± 0.04	1.24
8	528 ± 2	153 ± 6	-1.29 ± 0.03	1.08
9	459 ± 2	155 ± 7	-1.70 ± 0.04	0.81
10	76 ± 1	582 ± 250	-2.52 ± 0.08	0.15
11	756 ± 3	138 ± 6	-1.30 ± 0.04	1.46
12	499 ± 3	182 ± 24	-1.79 ± 0.09	0.92
13	236 ± 4	299 ± 67	-2.16 ± 0.09	0.45
14	497 ± 4	188 ± 25	-1.64 ± 0.09	0.98
15	516 ± 4	129 ± 13	-1.43 ± 0.09	0.92
16	698 ± 3	137 ± 8	-1.16 ± 0.05	1.42
17	715 ± 4	124 ± 7	-1.01 ± 0.06	1.45

^a Integral luminosity in the 60 keV–MeV band.

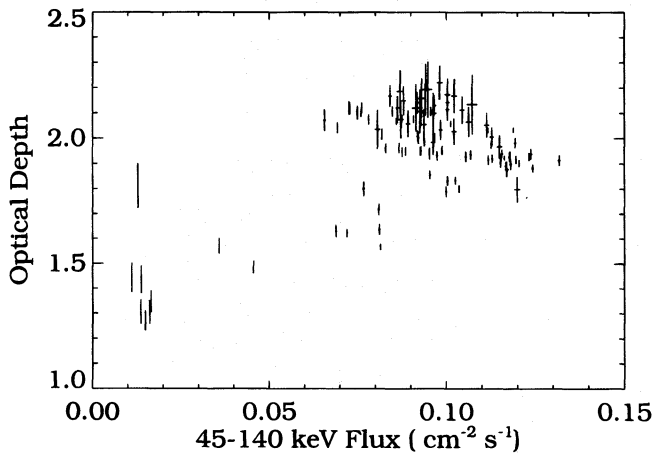


FIG. 4.—Optical depth vs. 45–140 keV integrated flux for each day, using the model of Sunyaev & Titarchuk (1980), with the temperature fixed at 65 keV.

temperature–low-amplitude regime. During the very low flux observation of 1994 February, the temperature of the source was ~ 70 keV, compared with 140 keV for the other observations. Note that the scatter in the points on this

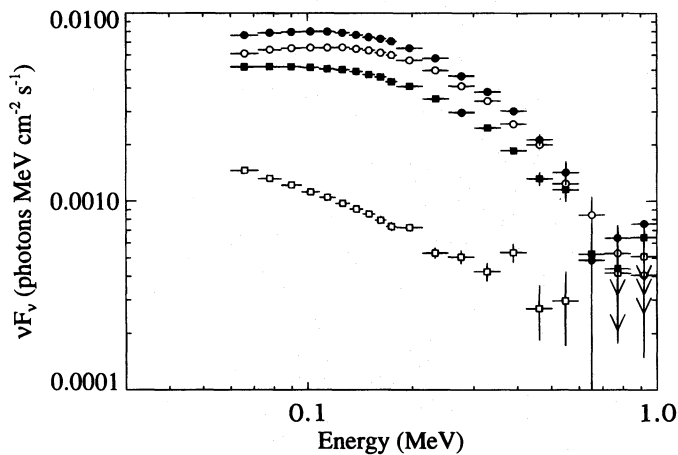


FIG. 5.—Photon spectrum multiplied by the energy squared. The data were grouped into four bins according to their 45–140 keV flux: fewer than 0.06 photons $\text{cm}^{-2} \text{s}^{-1}$, between 0.06 and 0.08 photons $\text{cm}^{-2} \text{s}^{-1}$, between 0.08 and 0.105 photons $\text{cm}^{-2} \text{s}^{-1}$, and more than 0.105 photons $\text{cm}^{-2} \text{s}^{-1}$.

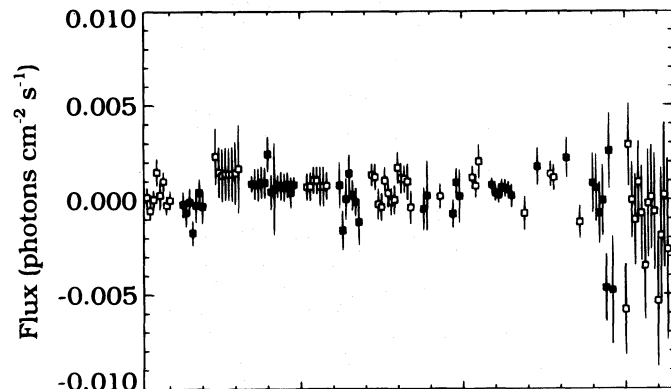


FIG. 6a

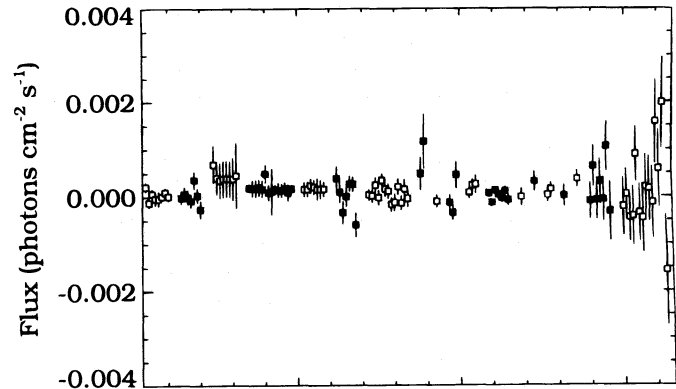


FIG. 6b

FIG. 6.—Amplitude and error of the 1 MeV Gaussian fit (Fig. 6a) and the narrow 511 keV line (Fig. 6b) on top of a thermal bremsstrahlung continuum for each day of data. The X-axis is the same discontinuous time axis as in FIG. 1.

figure and the following figures is much larger than the statistical or systematic errors. Alternatively, fitting the daily data with the thermal Comptonization model derived by Sunyaev & Titarchuk (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. With the temperature fixed at 65 keV, the optical depth–intensity distribution is as shown in Figure 4.

In Figure 5, we display spectra in terms of $E^2\Phi(E)$ in order to highlight the energy of peak power output in the OSSE band, and to 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 photons $\text{cm}^{-2} \text{s}^{-1}$. 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 photons $\text{cm}^{-2} \text{s}^{-1}$, respectively. The low-amplitude spectra are more like a power law than the other data. If a power law is assumed for the observation with the lowest amplitude spectrum, observation 10, the best fit is for an amplitude of $(7.5 \pm 0.1) \times 10^{-2}$ photons $\text{cm}^{-2} \text{s}^{-1} \text{MeV}^{-1}$ at 100 keV and a power-law index of -2.72 ± 0.03 with a χ^2 probability of 0.3.

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. Near the $\gamma 1$ flux level, an increase in the fit 1 MeV amplitude would be expected. The fit amplitudes are shown in Figure 6a. 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 2, the 90% confidence level (CL) upper limit to the 1 MeV line is 4×10^{-4} photons $\text{cm}^{-2} \text{s}^{-1}$, compared to the flux of 1.6×10^{-2} photons $\text{cm}^{-2} \text{s}^{-1}$ measured by Ling et al. The 95% CL upper limit for a 1–1.5 MeV wide feature near 4 MeV is 2.0×10^{-5} photons $\text{cm}^{-2} \text{s}^{-1}$.

The search for lines can be repeated at any energy and width. Given the previous reports of a narrow 511 keV line, we fit the data for a narrow (less than the instrument

resolution) 511 keV line for each day of data. These results are shown in Figure 6*b*. We do not find any days with a significant excess 511 keV emission, or 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 1.0×10^{-3} photons $\text{cm}^{-2} \text{s}^{-1}$ for most days. The 90% CL upper limit for a narrow 511 keV in the total spectrum is 7×10^{-5} photons $\text{cm}^{-2} \text{s}^{-1}$.

Since Ramaty et al. (1981) predict a broad 511 keV feature (FWHM ~ 160 keV), we also searched for a 160 keV wide peak at 511 keV. The results show no significant positive detections. The fit flux values for the broad line are significantly larger than for the narrow line, because the broad line has a larger effect on the underlying continuum spectrum represented by a thermal bremsstrahlung model. Still, the derived flux values provide new limits to theoretical models with a 90% CL upper limit of $(1-3) \times 10^{-3}$ photons $\text{cm}^{-2} \text{s}^{-1}$ for most days. The 90% CL upper limit for a broad 511 keV feature in the total spectrum is 2×10^{-4} photons $\text{cm}^{-2} \text{s}^{-1}$.

6. DISCUSSION

The variability of Cyg X-1 at gamma-ray energies, as seen in Figure 1, 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 behavior observed in GRO J0422 + 32, where the temperature is monotonically increasing in time as the transient decreases in brightness (Kroeger et al. 1996).

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, might fit both sets of data simultaneously (Gierlinski et al. 1996). Using the exponentially truncated power-law model to find the maximum in the luminosity per decade, and correlating that with the luminosity in the 60 keV–1 MeV band, the relationship shown in Figure 7 is obtained. The maximum in the distribution of luminosity per decade seems correlated to the total luminosity. The spectrum for the lowest intensity observation, observation 10, is then interpreted as the same model with a maximum at $\ll 60$ keV in the distribution of luminosity per decade, instead of the more typical 160 keV, causing the power-law-like appearance of this spectrum.

Extrapolating the exponentially truncated power-law model to lower energies, we find that the calculated flux in the 3–11 keV range for observation 10 (the lowest intensity observation in the OSSE energy band) is ~ 3 times larger than for observation 1, a typical observation. This anticorrelation between the extrapolated low-energy X-ray flux and the measured gamma-ray flux is consistent with earlier observations (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, depending on which spectra are compared.

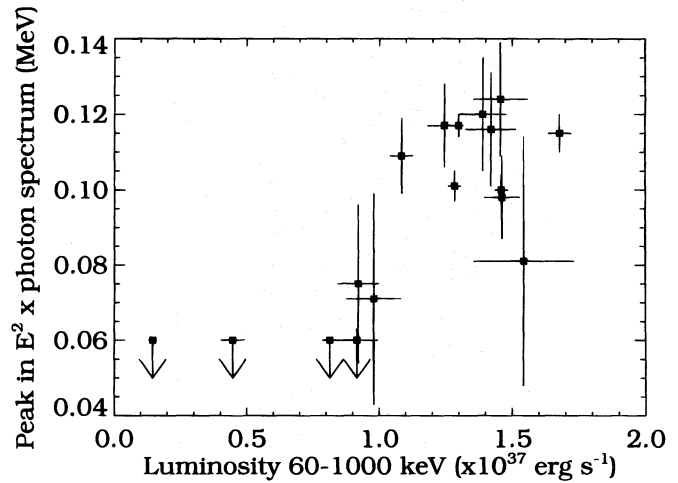


FIG. 7.—Peak in luminosity per decade vs. luminosity between 60 and 1000 keV for the model fits of all the observations, as in Table 3.

We have searched for the amplitude of a broad MeV bump, a narrow 511 keV line, and a broad 511 keV line. The distribution of fit MeV amplitudes (Fig. 8) is Gaussian, with a small nonzero mean, indicating that the underlying thermal bremsstrahlung distribution underestimates the continuum flux at 1 MeV by $\sim 5 \times 10^{-4}$ photons $\text{cm}^{-2} \text{s}^{-1}$. 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 width of the distribution in Figure 8 is consistent with the uncertainty in the amplitudes histogrammed. Since no strong signal was found, upper limits are derived for such features. These upper limits are lower than previous measurements and constrain the models for Cyg X-1. The 90% confidence level upper limit to the 1 MeV bump flux is in the $(1-4) \times 10^{-3}$ photons $\text{cm}^{-2} \text{s}^{-1}$ range for most days. This clearly demonstrates that the MeV bump is not systematically associated with the $\gamma 1$ state. If MeV bumps of the intensity reported by Ling et al. 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

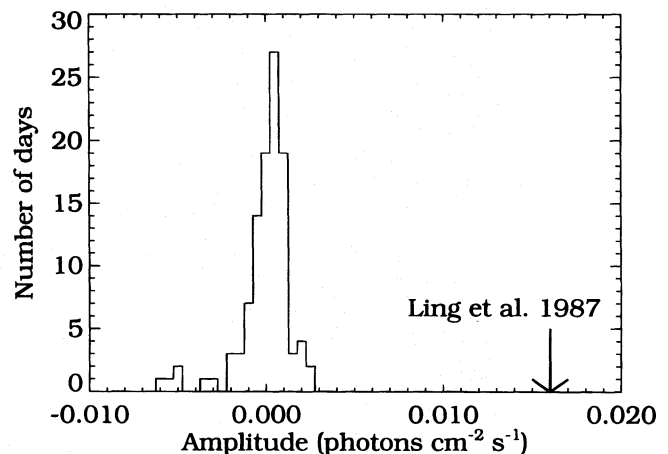


FIG. 8.—Distribution of the daily amplitudes of the 1 MeV Gaussians. Amplitude reported by Ling et al. (1987) is shown for comparison.

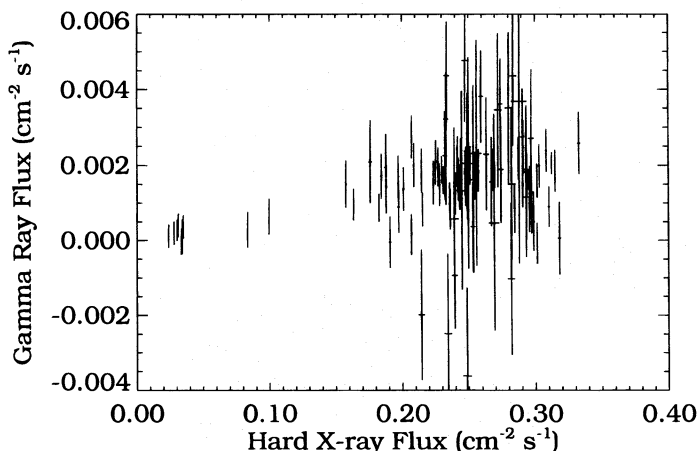


FIG. 9.—Flux in the 0.4–1.5 MeV band vs. the flux in the 0.06–0.4 MeV band for each day of data. These bands are nearly identical to those in the compilation of Bassani et al. (1989).

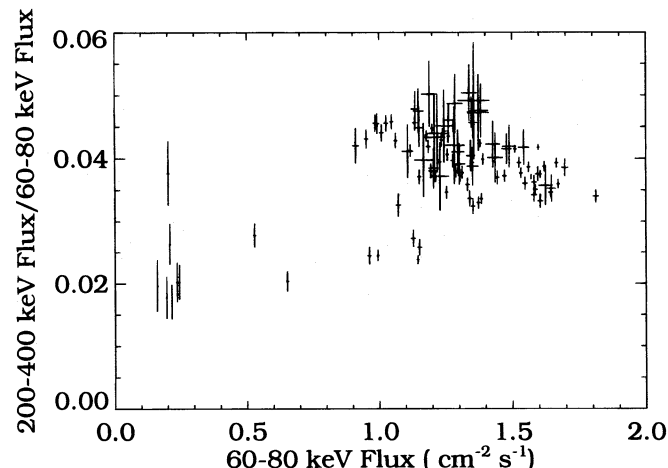


FIG. 10.—Ratio of the flux in the 200–400 keV band to the flux in the 60–80 keV band vs. the flux in the 60–80 keV band for each day of data.

25 outbursts over the first 3 years of the mission. For 4 day episodes the duty cycle must be less than 4.5%, and for 14 day episodes the duty cycle must be less than 9%, which corresponds to ~ 6.5 outbursts over the mission so far. Harris, Share, & Leising (1994) obtained a 95% confidence upper limit of 4.1% on the duty cycle for 12 day episodes.

According to the models of Dermer & Liang (1989) and the compilation of data by Bassani et al. (1989), there would 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, and plotted the high-energy band versus the low-energy band, in order to have a direct comparison with Bassani et al. (Fig. 9). 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. This is consistent with our earlier interpretation of higher temperature at higher flux. The anticorrelation modeled by Dermer & Liang was for a fixed accretion rate. However, it is likely that the changes measured are due to a change in accretion rate. In that case, the predicted hard X-ray and gamma-ray components would rise and fall together and would be correlated, as observed. The correlation coefficient for these data, when weighted by and including only the error in the high-energy flux, is 0.72, corresponding to a probability that the variables are not correlated of less than 0.01. If only data with hard X-ray flux greater than $0.20 \text{ photons cm}^{-2} \text{ s}^{-1}$ are considered, the correlation coefficient of this ratio is 0.03, implying no correlation between the fluxes during most observations.

The 0.4–1.5 MeV band is not optimized for daily OSSE observations of Cyg X-1, since the source is not detected beyond $\sim 800 \text{ keV}$ on a daily basis. The energy band was selected to provide a direct comparison with the analysis of Bassani et al. To better check our compatibility with the model of Dermer et al. that postulates a pivot near 100 keV , we have derived the hardness ratio between the 200–400 keV band and the 60–80 keV band. A spectral shape independent of amplitude would produce a horizontal line in this plot, and the expected anticorrelation would be seen as a decreasing curve. From Figure 10, we see the same pattern as in the temperature-amplitude scatter plots. There is a positive correlation (correlation coefficient of 0.32) between the hardness ratio and the 60–80 keV flux for the low-amplitude points only ($< 0.7 \text{ photons cm}^{-2} \text{ s}^{-1}$ in the 60–80 keV band), again consistent with higher temperatures at higher flux. But for the dense, high hardness ratio cluster of data ($> 0.7 \text{ photons cm}^{-2} \text{ s}^{-1}$ in the 60–80 keV band and $> 0.035 \text{ photons cm}^{-2} \text{ s}^{-1}$ in the hardness ratio), there is an anticorrelation (correlation coefficient of -0.48) between the ratio and the low-energy flux.

We hope to shed further light on this correlation/anticorrelation pattern by acquiring more data on Cyg X-1 when it is at intermediate or very bright flux levels.

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