BATSE Observations of Cygnus X-1

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ABSTRACT

We report preliminary results of 65 days of BATSE: Earth-occultation observations of the low energy gamma-ray (20 keV - 1.8 MeV) emission of Cygnus X-1 covering the period from 23 April to 27 June 1991. Cygnus X-1 underwent two transitions in this period. The 45-140 keV flux was first observed between 23 April and 14 May. The source began a transition to \( \gamma_1 \) on 14 May and remained at approximately this level from 19 to 29 May, and then moved toward \( \gamma_2 \) and remained at approximately this level from 10 to 27 June. Both \( \gamma_1 \) (19-29 May) and \( \gamma_2 \) (19 - 27 June) spectra observed by BATSE can be best characterized by the Comptonized model with temperature of 67 keV and 62 keV, respectively, and optical depth of -2. There was no evidence for any broad spectral feature near 1 MeV seen previously by several satellite and balloon experiments. A composite Cygnus X-1 spectrum observed by BATSE and COMPTEL in Viewing Period 2 (31 May - 7 June) suggests that a power-law with index of -3.5 may best characterize the spectrum from 20 keV to several MeV.

INTRODUCTION

Cygnus X-1 is one of the strongest celestial low-energy gamma-ray (0.02 - few MeV) sources known to date. It has displayed long-term temporal and spectral variability which includes (1) hard x-ray (45 - 140 keV) flux variation among several levels (Ling et al. 1987; Ling 1988) with time scale ranging from days to months, (2) episodic broad spectral features in the 0.5 - few MeV region which have been interpreted as evidence for relativistic pair plasma in the accretion disk (Nolan & Matteson 1983; Ling et al. 1987; McConnell et al. 1989; Liang & Dermer 1988), and (3) a possible narrow 0.511 keV annihilation line feature correlated with the broad MeV feature (Ling & Wheaton, 1989) providing further supporting evidence for positron-electron pairs produced in the system. Several issues related to these observations remain unresolved. For example, what is the mechanism driving the long-term flux variation? Is there a pattern which may help explaining the physics responsible for such variability? Is the broad MeV feature real? If so, it needs to be confirmed. What is the mechanism responsible for the formation of such a pair plasma?

The Large Area Detectors (LAD's) of the BATSE experiment onboard the Compton Gamma-Ray Observatory (CGRO) are ideally suited to answer many of these questions. They have the capability to provide nearly uninterrupted monitoring of cosmic sources with unprecedented sensitivity using the Earth as an occultor for modulating the source signals (Harmon et al. 1992; Skelton et al. 1992). We have been monitoring Cygnus X-1 since...
Figure 1. The Cygnus X-1 light curve in the 45-140 keV energy band. Two data points are shown for each day, corresponding to measurements made by different IAD's. The uncertainties include both statistical and systematic contributions summed in quadrature.

launched using MSFC Mission OperationS (MOPS) analysis package (Harmon et al. 1992), and have found that the source made a number of transitions between the $\gamma_1$ and $\gamma_2$ levels during the first two and half years of the CGRO mission (Harmon et al. 1993a,b). Most of these data are currently being analyzed in detail using a new JPL "Enhanced" BATSE Occultation Package (EBOP) (Skelton et al. 1993, these Proceedings). EBOP is designed to improve the sensitivity of the analysis by using much more data to reduce statistical errors, together with detailed background modeling to control systematic error. In this paper, we present evidence for temporal and spectral variations associated with the first $\gamma_1-\gamma_2$ transition observed in June of 1991. These data were analyzed using primarily EBOP Version 1.1. As EBOP continues to improve in the months ahead, we expect these results to improve. Our present results should thus be considered somewhat preliminary. Improved results will be submitted for publication at a later date.

RESULTS

Flux Variations. Figure 1 shows the 45-140 keV light curve measured by BATSE from 23 April (TJD 8369) to 27 June (TJD 8434) of 1991. For the first 20 days in this
Figure 2. The overall $\gamma_1$ and $\gamma_2$ spectra observed by BATSE (bold lines) agree well with those of HIAO3 (Ling et al. 1987; thin dots/lines), the only discrepancy being the lack of the enhanced McV feature in the $\gamma_1$ spectrum (2a). The $\gamma_1$ spectrum is harder than $\gamma_2$ spectrum (Fig. 2b, shown as a dashed line in 2a) and intersects the latter at a few hundred keV.

period, except for one-day fluctuations. We found the source generally at a level between $\gamma_1$ and $\gamma_2$. However, starting at ~TJD8390 (14 May), the flux began to drop and reached the $\gamma_1$ level within a few days. It stayed at this level for approximately ten days (TJD 8395-8405) before ramping up toward $\gamma_2$ where it remained from TJD 8417 to 8434. The two data points shown for each day correspond to measurements made by two different LADs. The overall pattern of the temporal variability was therefore consistently and independently observed by two LADs. The uncertainty associated with each datum includes contributions from statistical and estimated systematic effects, summed in quadrature. The systematic errors dominate the statistical errors in this energy band by approximately a factor of 4 for this analysis (Skelton et al., 1993, these Proceedings). Their magnitudes have been estimated based on the consistency of the daily fluxes measured by two detectors over a period of ~70 days. While no rigorous treatment of the systematic error is possible, we believe the quoted errors to be conservative. As our analysis method continues to be improved and refined, we hope to reduce the systematic contribution.
Figure 3. The composite Cygnus X-1 spectrum measured by BATSE and COMPTEL consists possibly of two components: a Comptonized component in the 20-200 keV range followed by a power law extending to several MeV.

**Spectral Variations.** Figure 2 shows the time-averaged spectra measured during the $\gamma_1$ (TJD 8395-8405) and the $\gamma_2$ (TJD 8417-8434) periods, respectively. The solid lines are the best-fit Comptonized spectra (Sunyaev & Titarchuk 1980) with $kT = 67$ keV and $\tau = 2.0$ for the $\gamma_1$ spectrum, and $kT = 62$ keV and $\tau = 2.1$ for the $\gamma_2$ spectrum. We find no evidence for enhanced MeV emission associated with either the $\gamma_1$ spectrum as reported by Ling et al. (1987) or the $\gamma_2$ spectrum, suggesting that such MeV features may be independent of the hard x-ray states. The $\gamma_2$ spectrum (Figure 2b) is softer than the $\gamma_1$ spectrum and intersects the latter at around a few hundred keV, consistent with that observed by HEAO-3. Except for the lack of evidence for the MeV feature, both the $\gamma_1$ and $\gamma_2$ spectra observed by BATSE agree very well with those measured by HEAO3 in 1979-1980. Figure 3 shows a composite BATSE and COMPTEL (McConnell et al. 1993) spectrum for CGRO Viewing Period #2 (VP-2, TJD 8407-8415). The two spectra are quite consistent in regions where they overlap. It is interesting to note that contrary to our standard view of the Cygnus X-1 spectrum which has typically a Comptonized shape with a sharp cut-off above 300-400 keV, this composite spectrum seems to have two components: a Comptonized component in the 20-200 keV region followed by a power law, with index of -3.5, extending to several MeV.
CONCLUSION

Cygnus X-1 was observed to undergo dramatic changes in 1991-1993. Most of these data, specifically those after July 1991, are currently being analyzed using EBOP and these results will be published at a later date. We report here preliminary results of the first 60 days of observations covering the period from 23 April to 27 June 1991 using EBOP-Version 1.0. During this period, Cygnus X-1 was near both the $\gamma_1$ and $\gamma_2$ levels for 10 days and 17 days, respectively. The transition from $\gamma_1$ to $\gamma_2$ took about 10 days. Except for the absence of the broad MeV feature in the $\gamma_1$ spectrum which was observed by II:A03 in 1979, both $\gamma_1$ and $\gamma_2$ spectra agree very well with those observed by II:A03. A composite BATSE and COMPTEL spectrum observed in Viewing Period #2 indicates that the source spectrum may be characterized by a Comptonized component in the 20-200 keV range followed by a power law extending to several MeV.

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