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The MeV Gamma-Ray Spectrum of Cygnus X-1

M.L. McConnell[1], K. Bennett[2], H. Bloemen[3], W. Collmar[4], W. Hermsen[3], L. Kuiper[3], J.C. Ling[5], B. Phlips[6], J.M. Ryan[1], V. Schönfelder[4], H. Steinle[4], A.W. Strong[4]

[1] *Space Science Center, University of New Hampshire, Durham, NH 03824, USA*

[2]*Space Science Department, ESTEC, Noordwijk, The Netherlands*

[3]*Space Research Organization of the Netherlands (SRON), Utecht, The Netherlands*

[4]*Max Planck Institute for Extraterrestrial Physics (MPE), Garching, Germany*

[5]*Jet Propulsion Labortatory (JPL), Pasadena, CA and NASA Headquarters, Washington, DC*

[6]*Universities Space Research Association, Washington, DC 20024, USA*

Abstract

The COMPTEL experiment on the Compton Gamma-Ray Observatory (CGRO) has observed the Cygnus region on several occasions since its launch in 1991. These data represent the most sensitive observations to date of Cyg X-1 in the 0.75-30 MeV range. Here we report on the results of an analysis of selected COMPTEL data collected during the first three years of the CGRO mission. The integrated spectrum shows significant evidence for emission extending out to several MeV. These data are compared with contemporaneous data from both BATSE and OSSE.

1 Introduction:

It has become increasingly apparent over the last several years that the standard thermal Comptonization model (Sunyaev & Titarchuk 1980) does not provide an adequate description of the broad-band spectrum of Cyg X-1. Several modifications to the standard model have been proposed that seek to provide a better fit to the data. For example, modifications to the standard model have been developed which expand the range of allowable parameter space (e.g., Titarchuk 1994; Hua & Titarchuk 1995; Skibo et al. 1995). Other models have pursued alternative geometries that can also lead to improvements in the model. These include the incorporation of Compton backscatter radiation from a cooler optically-thick accretion disk (Haardt et al. 1993; Wilms et al. 1996) or models based on a thermally stratified geometry (e.g., Skibo & Dermer 1995; Ling et al. 1997a; Moskalenko, Collmar & Schönfelder 1998). Still others have proposed schemes which are based on nonthermal acceleration processes (e.g., Li, Kusunose & Liang 1996; Crider et al. 1997) or π° decay (Jourdain & Roques 1994). All of these models have their merits. Unfortunately, given the quality of the available data, it is difficult to determine a clearly favored candidate to account for the observed spectrum near 1 MeV. In this regard, the data collected by the instruments on CGRO offer the best opportunity for studying the high energy spectrum of Cyg X-1.

2 Observations and Data Analysis:

To date, COMPTEL has obtained numerous observations of the Cygnus region. Most of the high-quality (i.e., near on-axis) observations took place during the first three years of the mission. Here, we have selected a subset of these data for analysis (Table 1). This choice of observations was dictated by the availability of contemporaneous OSSE. These data, along with contemporaneous results from BATSE, were used to assemble a broad-band spectrum extending well above 1 MeV. Discrepancies in the initial comparison of the three spectra (McConnell et al. 1997) were later attributed to variations in the source spectrum coupled to variations in the relative exposure time of each instrument. Consequently, data from some of these observations (VP 318.1 and VP 331.5) were later excluded from the analysis, based on the level of hard X-ray flux as measured by BATSE occultation analysis (Figure 1). This selection insures that all data were collected while Cyg X-1 was in the same spectral state.

TABLE 1 – SELECTED CGRO OBSERVATIONS

Viewing Period	Start Date	Start TJD	End Date	End TJD	Viewing Angle	Effective Exposure
2.0	30-May-1991	8406	8-Jun-1991	8415	1.7°	3.65
7.0	8-Aug-1991	8476	15-Aug-1991	8483	11.2°	2.72
203	1-Dec-1992	8957	22-Dec-1992	8978	7.0°	5.19
212.0	9-Mar-1993	9055	23-Mar-1993	9069	15.4°	2.71
318.1	1-Feb-1994	9384	8-Feb-1994	9391	4.5°	1.78
328.0	24-May-1994	9496	31-May-1994	9503	7.0°	1.56
331.0	7-Jun-1994	9510	10-Jun-1994	9513	7.0°	0.95
331.5	14-Jun-1994	9517	18-Jun-1994	9521	7.0°	1.34
333.0	5-Jul-1994	9538	12-Jul-1994	9545	7.0°	1.86

The analysis of COMPTEL data involves generating a series of images, one for each energy interval of interest. Assumptions regarding the spectral shape are incorporated into the point-spread-functions (PSFs) used in the analysis of each image. Flux values derived from each image are used to compile a spectrum of the source. The resulting spectrum is then compared versus that assumed for the PSF generation to insure a consistent analysis. The COMPTEL image analysis for Cyg X-1 is complicated by the fact that we are looking in the galactic plane. Images generated with COMPTEL data generally show some level of spatial structure, much of which is believed to result from galactic diffuse emission. In the present case, the spatial analysis of each energy interval was performed independently using a variety of spatial distributions. These

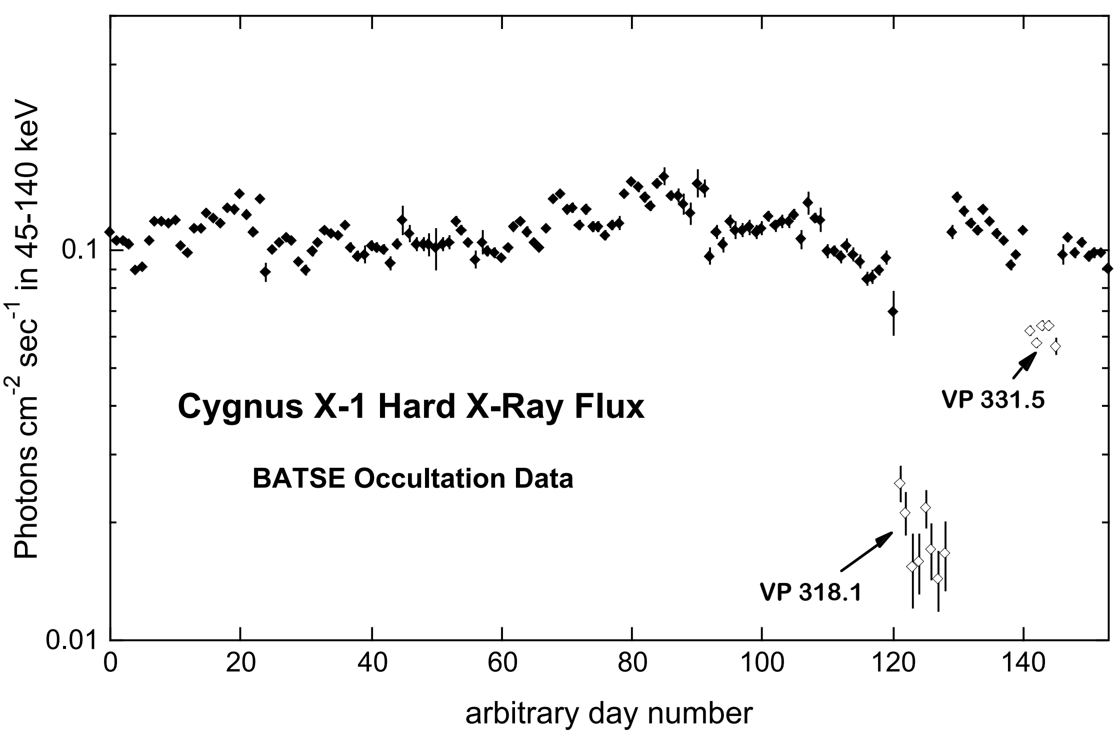

Figure 1: The hard X-ray flux of Cyg X-1 as measured by BATSE occultation monitoring for those days represented by the observations in Table 1. The two observation periods with relatively low hard X-ray flux were excluded from the final analysis.

included models for the expected distribution of the galactic diffuse emission (based on the known gas distributions) and also empirical modeling using a superposition of one or more sources. Models for PSR 1951+32 (located 2.6° away from Cyg X-1) were also included in the analysis. This pulsar has been detected by EGRET and there is evidence (based on a joint timing and spatial analysis) for it in the COMPTEL data as well (Kuiper et al. 1998). Variations in the derived flux using different spatial models provided a handle on the systematic uncertainties in the analysis.

The COMPTEL data for Cyg X-1 (accumulated from the viewing periods listed in Table 1) shows clear evidence for emission extending out to at least 2 MeV and perhaps as high as 5 MeV. The COMPTEL data alone can be modeled as a power law spectrum with a photon index of -3.7. Good fits can also be obtained using Comptonization models (with electron temperatures in the range of 450-700 keV), but the extrapolation of these fits to lower energies is quite poor. The COMPTEL spectrum is shown along with contemporaneous BATSE and OSSE data in Figure 1. The BATSE spectrum in this case was derived using the JPL Enhanced BATSE Occultation Package (EBOP; Ling et al. 1997b.) These lower-energy data provide the constraints needed for a more effective interpretation of the COMPTEL data.

4 Discussion:

The COMPTEL data alone seems to further corroborate the conclusion that standard thermal Comptonization models may be inadequate in describing the observed spectrum – Comptonization models fall off far too rapidly near 1 MeV (see also McConnell et al., 1994; Ling et al. 1997a). Fits to the combined

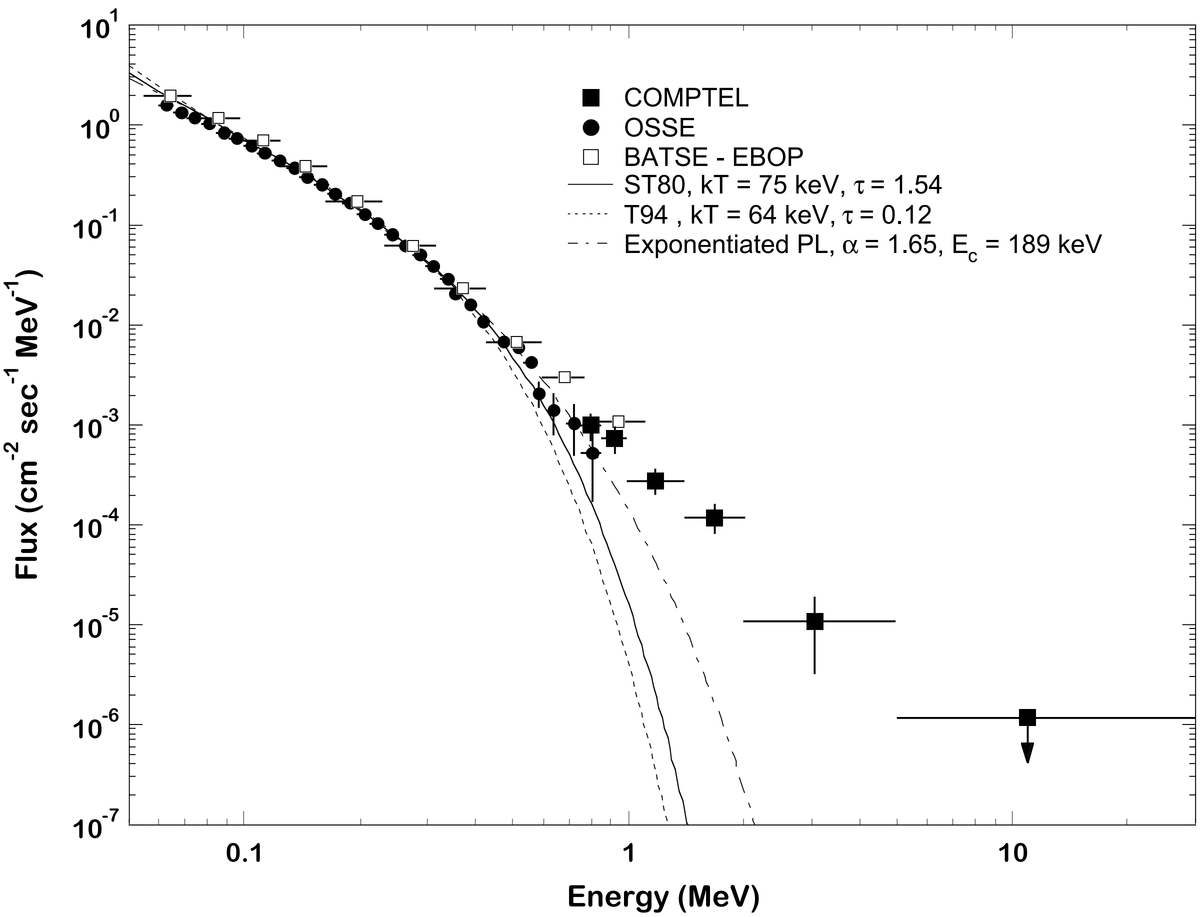

Figure 2: The broad-band spectrum of Cyg X-1 as measured by BATSE, OSSE and COMPTEL. Upper limit data points for BATSE and OSSE have been removed for clarity.

BATSE/OSSE/COMPTEL data provide further evidence for this conclusion. In Figure 2, we show the best-fit spectra (over the full range from 50 keV to 5 MeV) based on the Comptonization model of Sunyaev & Titarchuk (1980), the generalized Comptonization model of Titarchuk (1994) and an empirical fit using an exponentiated power-law (c.f. Phlips et al. 1996). Although the Sunyaev & Titarchuk (1980) model provides a better broad-band fit to the data, the resulting parameters lie outside the range of applicability for this model (Skibo et al. 1995). The model of Titarchuk (1994) may therefore provide a more physically correct fit to the data. Improved fits with the Comptonization models can be obtained by limiting the fit to energies above ~300 keV. The fits obtained by fitting only at energies above 300 keV may, in the context of the reflection models, be a more realistic estimate of the electron temperature, since reflection would contribute to the spectrum only at energies below ~300 keV. On the other hand, several other models can also produce a hard tail feature near 1 MeV without the need for a reflection component. These include both the two-temperature models (Skibo & Dermer 1995; Ling et al. 1997a; Hua, Ling & Wheaton 1997; Moskalenko, Collmar & Schönfelder 1998) and nonthermal models which involve inverse Comptonization of an electron population consisting of both a Maxwellian and some non-Maxwellian distribution (e.g., Li, Kususnose & Liang 1996; Crider et al. 1997). Continued analysis of these data may help shed light on the underlying nature of the high energy emissions from Cyg X-1 and other black hole sources, such as GRO J0422+32, which also shows evidence for a hard tail near 1 MeV (van Dijk et al. 1995).

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