

1.0 INTRODUCTION

Cyg X-1 is one of the most intriguing gamma-ray sources in the sky. In addition to being one of the brightest sources in the sky at energies around 1 MeV, it is the archetypal stellar mass black hole candidate. A thorough understanding of this source will surely have an impact on our understanding of all black hole sources, from the (stellar mass) soft X-ray transients to the (supermassive) Active Galactic Nuclei (AGN). The history of Cyg X-1 is riddled with several reports of emission in the region around 1 MeV which far exceeded that which would be expected from a simple extrapolation of the low energy spectrum – the so-called “MeV bump” (e.g., Ling et al., 1987; McConnell et al., 1989). Both the COMPTEL and OSSE experiments on CGRO have failed to confirm emission levels as reported by some of these earlier observations (McConnell et al., 1994, 1997; Philips et al., 1996). The CGRO data have, however, confirmed the fact that the broad-band emission (100 keV up to ~2 MeV) is not well-fit by a single-temperature Comptonization model. Relative to standard Comptonization models, the spectrum hardens considerably near 1 MeV. *We propose a continued analysis of CGRO data that will provide a high sensitivity measurement of the spectrum to beyond 1 MeV, maximizing the return of archival CGRO data.*

2.0 SCIENTIFIC JUSTIFICATION

For many years, the standard spectral model for Cyg X-1 and other black hole candidates has been the inverse Compton model of Sunyaev and Titarchuk (1980). Based on the disk accretion of matter onto a black hole, this analytical model is quite successful in describing the spectrum of many black hole candidate sources, including that of Cyg X-1, up to ~300 keV. High quality spectra of Cyg X-1 at higher energies (300 keV - 1 MeV) has only become available in the last few years. These data, most notably those obtained with SIGMA (Grebenev et al. 1993) and OSSE (Philips et al. 1996), now clearly indicate that a single-component Sunyaev-Titarchuk model does a poor job of describing the full spectrum up to ~1 MeV. In particular, the observed spectrum appears harder than that predicted by the S-T model. Several models have been discussed in the literature which seek to explain this hard X-ray tail. For example, Titarchuk (1994) developed an analytic model which extends the range of validity of the Sunyaev-Titarchuk model to include the range of optical depths encompassing the observations. Haardt et al. (1993) developed a model which incorporates a hard X-ray component arising from the scattering of photons off an optically thick region of the accretion disk (see also Done et al. 1992). Thermal stratification within the accretion region has also been proposed to provide an improved fit to the broad band spectrum (e.g., Liang & Dermer 1988; Skibo & Dermer 1995; Ling et al. 1997; Misra et al. 1997). Jourdain & Roques (1994) have suggested an emission component near 1 MeV based on pion decay. It has also been shown that a non-thermal tail in the electron distribution can lead to a hard X-ray tail that is more consistent with the observed spectrum (e.g., Li, Kusunose & Liang 1996; Li & Miller 1997; Crider et al. 1997; Moskalenko et al. 1998). *The spectrum at energies above 1 MeV can be most useful in defining the exact shape of the hard tail. Only then can we hope to distinguish between the various spectral models.*

Data from COMPTEL offer our best hope for precisely defining the highest energy parts of the spectrum. The analysis of COMPTEL data for Cyg X-1 has been complicated by the fact that it lies within the galactic plane and that there is considerable structure in the COMPTEL images of this region. In addition, allowance must be made for the presence of PSR 1511-32, which lies only 2.6° away and also appears to be a source of MeV γ -rays (Kuiper et al. 1998). These obstacles have been largely overcome and there is now a high degree of confidence in the resulting spectra. A proper interpretation of COMPTEL spectra, however, requires a comparison with spectra at lower energies. A broad-band CGRO spectrum based on contemporaneous data from COMPTEL, OSSE and BATSE is shown in Figure 1. An earlier version of this composite spectrum (McConnell et al. 1997) showed a discrepancy at low energies between the OSSE and BATSE spectra. This was only very recently traced to variations in the relative exposure of each instrument, coupled to intrinsic variations in the source itself. In order to produce this composite spectrum, observation time intervals were selected (from phases 1–3 of the CGRO mission) in which all three instruments were observing the source and in which the hard X-ray flux was at a similar level (c.f., Figure 2).

The composite spectrum exhibits a nearly power-law shape extending out to at least 2 MeV and perhaps to near 5 MeV. (The highest energy COMPTEL data point at 10-30 MeV does not appear to represent a significant detection.) A detailed study of this spectrum is now in progress, but it is clear that a standard Comptonization model does not adequately account for the full spectrum. Some type of hard tail component appears to be required.

Observations with OSSE have demonstrated evidence for two distinct classes of black hole spectra based on the form of the spectra at energies above ~50 keV (Grove et al. 1997, 1998). One class (corresponding to the

traditional soft X-ray “high” state) exhibits a single continuous power law out to the limit of detectability (>200 keV), with peak luminosity below 10 keV. A second class (corresponding to the traditional soft X-ray “low” state) exhibits exponentially breaking spectra, with peak luminosity around 100 keV. These states have also been termed the γ -ray low and high states (Grove et al. 1997, 1998), respectively. It has been suggested that these two classes correspond to two distinct Comptonization mechanisms (Ebisawa, Titarchuk & Chakrabarti 1996). Such bispectral forms are also exhibited by Cyg X-1. The spectrum represented by Figure 1 corresponds to the high γ -ray state of Grove et al. (1997, 1998), i.e., the ‘low’ soft X-ray state. Cyg X-1 spends a large fraction of its time in this spectral state. There have, however, been at least two occasions during the CGRO mission in which COMPTEL observed Cyg X-1 in its low γ -ray state (near TJD 9400 and TJD 12500, as can be seen in Figure 2).

3.0 PROPOSED WORK FOR CYCLE 8

To date, the analysis of COMPTEL data for Cyg X-1 has concentrated on obtaining a CGRO-wide composite spectrum, in part to demonstrate the reliability of the COMPTEL spectral analysis. Such an analysis required using only those observations in which all three instruments were observing Cyg X-1. A further constraint was required to insure that Cyg X-1 was always in the same spectral state (as judged by the level of 45–170 keV emission). *Now that this cross-calibration has been demonstrated (Figure 1), we would like to move forward in an effort to maximize the scientific return from the COMPTEL data.* Towards this end, we propose to generate spectra with substantially better statistics. In addition, it would be of great interest to obtain similar spectra for other spectral states of the source. *We therefore propose to continue our efforts to analyze these data in such a manner that a more coherent picture of the MeV emission can be obtained.*

Figure 2 shows the level of hard X-ray emission for those days in which COMPTEL has observed Cyg X-1. (This plot is complete through the middle of cycle 6.) The days that were used to generate the spectrum in Figure 1 are shown as open circles. It is clear that Figure 1 represents only a small fraction of the total COMPTEL data. It is also clear that there is COMPTEL data available for other spectral states. We can therefore expect to learn much more about the MeV emission from Cyg X-1 with a more complete analysis of all COMPTEL data. Unfortunately, many COMPTEL observations of Cyg X-1 are not accompanied by simultaneous OSSE observations. *So in order to take full advantage of the COMPTEL data, we must relax the requirement for contemporaneous OSSE data.* BATSE data, on the other hand, are always available and can therefore be used to generate the broad-band spectra for those epochs when OSSE data is not available.

Spectra from BATSE data can be generated by using standard Earth occultation techniques or by using the JPL Enhanced Earth Occultation Package (EBOP; Ling et al. 1996). The standard Earth occultation approach uses only those data collected near the time of each occultation step and is limited to deriving reliable source spectra at energies below a few hundred keV. The EBOP algorithm makes use of all source data (even those data at large geocentric angles) by performing a multi-parameter fit (including 65 point sources) to the time-series data. With the EBOP, spectra for Cyg X-1 can typically be derived for energies much higher than the standard Earth occultation algorithm.

For cycle 8, we propose to continue our analysis of archival COMPTEL data for Cyg X-1 and to generate broad-band spectra using data from BATSE and, when appropriate, OSSE. We would also include constraints at higher energies from EGRET data to complete the γ -ray picture of Cyg X-1. In particular, we propose to do the following:

- 1) *Generate three COMPTEL spectra, with the data being selected on basis of the hard X-ray flux.* Specifically, we would generate COMPTEL spectra for times when the BATSE 45–170 keV flux was in the ranges of $< 0.06 \text{ cm}^{-2} \text{ s}^{-1}$, $0.6\text{--}0.15 \text{ cm}^{-2} \text{ s}^{-1}$, and $> 0.15 \text{ cm}^{-2} \text{ s}^{-1}$ (c.f., Figure 2). This analysis would cover all of the available flight data.
- 2) *BATSE spectra would be generated from the same time intervals using both the standard occultation algorithm and the JPL-EBOP algorithm.* The use of both algorithms provides a consistency check at lower energies. At present, EBOP spectra are only available through the end of phase 3. For later times the EBOP software will have to be resurrected at JPL or else spectra from the standard occultation analysis alone would have to be used.
- 3) *Generate OSSE spectra using whatever OSSE data is available from the same time intervals.* Our experience in generating the spectrum in Figure 1 underscores the need to compare only compatible spectra, especially when considering a source that is as variable as Cyg X-1.

4) *Determine the flux level (or upper limit to the flux level) using EGRET data for these same time periods.*

This analysis will concentrate on those data which are already available or that will be available by the end of cycle 7. Although we are not specifically requesting any new observations, we would like to incorporate into our analysis any new observations that may become available during cycle 8. *The results of this analysis effort should provide our best measurement yet of the MeV spectrum and how it connects to the hard X-ray spectrum. These data should provide a useful input to theoretical modeling of the broad-band spectrum of Cyg X-1.*

The proposed funding level of \$15,000 will be used to support the analysis of CGRO data (which may also include the resurrection of the JPL-EBOP software) and to prepare publications resulting from the analysis of these data.

References

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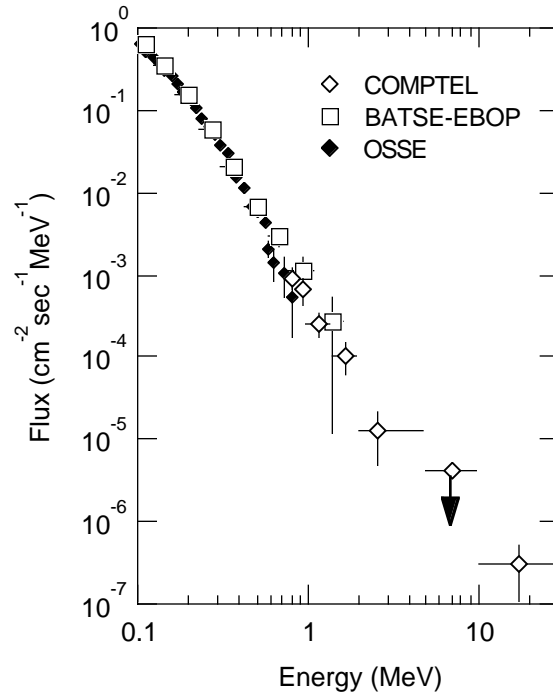


Figure 1 : Spectrum of Cyg X-1 from contemporaneous CGRO observations during the first three phases of the CGRO mission. OSSE data points above 900 keV (mostly upper limits) have been removed for clarity.

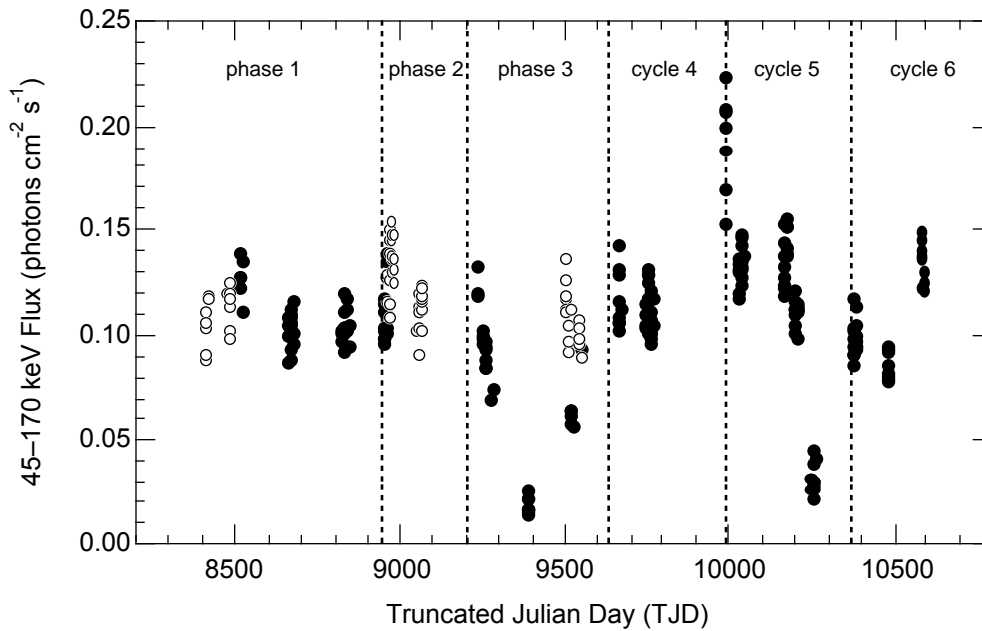


Figure 2 : Hard X-ray flux as measured by BATSE for each day of COMPTEL observation. Open circles indicate those days that were used to generate the spectrum in Figure 1.