

RECENT RESULTS FROM
COMPTEL OBSERVATIONS OF CYGNUS X-1

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ABSTRACT

The COMPTEL experiment on the Compton Gamma-Ray Observatory (CGRO) has now observed Cygnus X-1 on four separate occasions during phase 1 and phase 2 of its orbital mission (between April, 1991 and August, 1993). Here we report on the results of the latest analysis of these data, which provide a spectrum extending to greater than 2 MeV. A spectral analysis of these data, in the context of a classical Comptonization model, indicates an electron temperature much higher than previous hard X-ray measurements would suggest (200 keV vs 60-80 keV). This implies either some limitations in the standard Comptonization model and/or the need to incorporate a reflected component in the hard X-ray spectrum. Although significant variability near 1 MeV has been observed, there is no evidence for the 'MeV excess' which has been reported by some previous experiments.

INTRODUCTION

The COMPTEL experiment on the Compton Gamma-Ray Observatory is designed to measure gamma-radiation in the energy range from 0.75-30 MeV (Schönfelder et al. 1993). This is a particularly interesting energy range for the black-hole candidate Cygnus X-1. In recent years, data from several experiments have suggested that the single-temperature Sunyaev-Titarchuk Comptonization model may be inadequate to explain the hard X-ray data between several hundred keV and 1 MeV (e.g., Grebenev et al. 1993; Grabelsky et al. 1993). In addition, some observers have also reported the detection of a significant spectral hardening (to about E^{-1}) at energies above 1 MeV (e.g., Baker et al. 1973; Ling et al. 1987; McConnell et al. 1989). The measured spectra of this 'MeV excess' are clearly inconsistent with a simple extrapolation of the hard X-ray spectrum below 1 MeV. The reported flux levels are more than two orders of magnitude above the COMPTEL detection threshold, suggesting that COMPTEL would be capable of studying such emission in detail. Here we shall present the latest results from the analysis of the COMPTEL data and compare these results with other measurements at these energies.

OBSERVATIONS AND ANALYSIS

A total of roughly seven weeks of observation time on Cygnus X-1 has been collected during the first two phases (28 months) of the CGRO mission. These data were collected during six separate viewing periods as shown in Table 1. (Note that periods 203.0 - 203.6 represented only a change in the spacecraft orientation about its z-axis, rather than a change in the actual pointing direction. So in the present analysis, we treat these as a single observation.) In all cases, Cygnus X-1 was within 15° of the COMPTEL pointing direction, thus providing an excellent exposure.

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TABLE 1

Observation Period	Dates	Angle from z-axis
2.0	May 30 - June 8, 1991	2°
7.0	August 8-15, 1991	11°
203.0	December 1-8, 1992	7°
203.3	December 8-15, 1992	7°
203.6	December 15-22, 1992	7°
212.0	March 9-23, 1993	15°

The present analysis follows that described by McConnell et al. (1994). In particular, we have analyzed the data in six separate energy intervals: 0.75-0.85 MeV, 0.85-1.0 MeV, 1.0-2.0 MeV, 2.0-5.0 MeV, 5.0-10.0 MeV, and 10.0-30.0 MeV. For each observation, the data in each of these six energy intervals are analyzed using a maximum likelihood approach (de Boer et al. 1991). This analysis incorporates an instrumental point-spread-function (PSF) which is generated based on some assumed source spectrum. In the study of Cygnus X-1, we generally employ PSFs based on a Wien spectrum, which represents the high energy limit of the Sunyaev-Titarchuk Comptonization model (Sunyaev and Titarchuk 1980). For the datapoints above 5 MeV (where the Wien spectrum falls off very steeply), the analysis has employed PSFs based on an E^{-2} power law spectrum.

For the present analysis, no independent estimate of the background (predominantly instrumental in origin) was available for the maximum likelihood analysis. Therefore, an estimate of the background was derived directly from the source data by an averaging technique which suppresses point-source signals, but preserves the general background structure (Bloemen et al. 1993).

The analysis of each energy interval results in a flux value corresponding to that energy range. Once the results from each energy range are available, a photon spectrum can be compiled. A fit of the data in photon space is used to derive a corresponding electron temperature. Here, a consistency check can also be made to insure that the electron temperature used in deriving the PSFs corresponds to that derived from the spectral fit. Here, several different PSFs were used to derive the most consistent results. The final spectral results used a PSF for $kT = 200$ keV, which is consistent with the fitted value.

RESULTS

We have previously reported on the results from an analysis of the phase 1 data (periods 2.0 and 7.0; McConnell et al. 1993, 1994). These data indicated a firm detection of the source up to 2 MeV. The analysis of the individual observations shows a very similar spectrum in all cases. Indeed, the derived electron temperatures are all in the range of 180-220 keV. Our data also show that the flux around 1 MeV is variable on a time scale of several weeks. This can be seen in Figure 1, where we plot the integrated 0.75-2.0 MeV flux versus time for each of the four observation periods. Although the flux levels for periods 2.0, 203 and 212.0 are roughly equivalent, the flux level for period 7.0 is about a factor of two higher. This variation is roughly similar to that observed by BATSE near 100 keV (Ling et al. 1994).

In addition to analyzing the data from the individual observation periods, we have combined all seven weeks of data into one single spectrum. This spectrum is shown in Figure 2 along with other representative spectra from previous experiments. The electron temperature derived from these data is $kT = 190 \pm 20$ keV. One interesting aspect of the COMPTEL spectrum is that the 2-5 MeV datapoint is significant at the 3.5σ level. In order to confirm this detection, it is instructive to look at the imaged data. Figure 3 shows the imaged data from the 0.75-1.0 MeV energy band. A clear signal (with 12σ significance) is seen at the location of Cygnus X-1. A similar image for the 2-5 MeV interval also shows a point-like feature which is consistent with the location of Cygnus X-1. This confirms that we have indeed detected Cygnus X-1 at energies above 2 MeV.

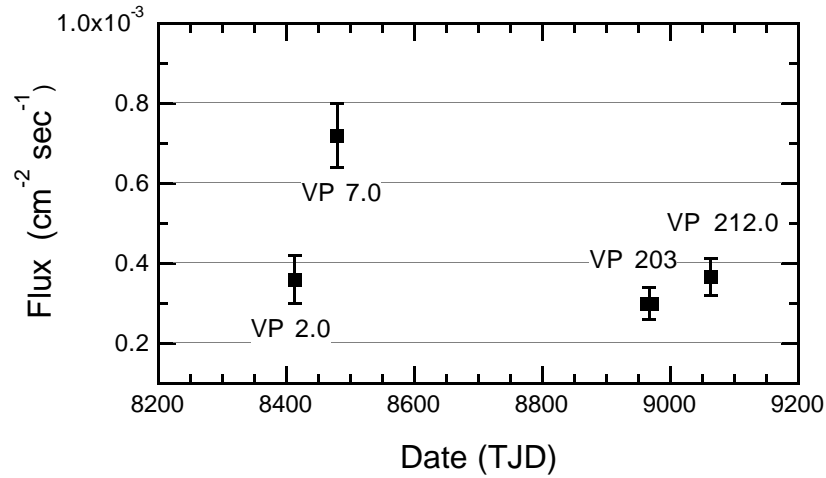


Fig. 1. The integrated flux in the 0.75-2.0 MeV energy interval for each of the four observations of Cygnus X-1. The higher flux level in viewing period 7.0 is clearly seen.

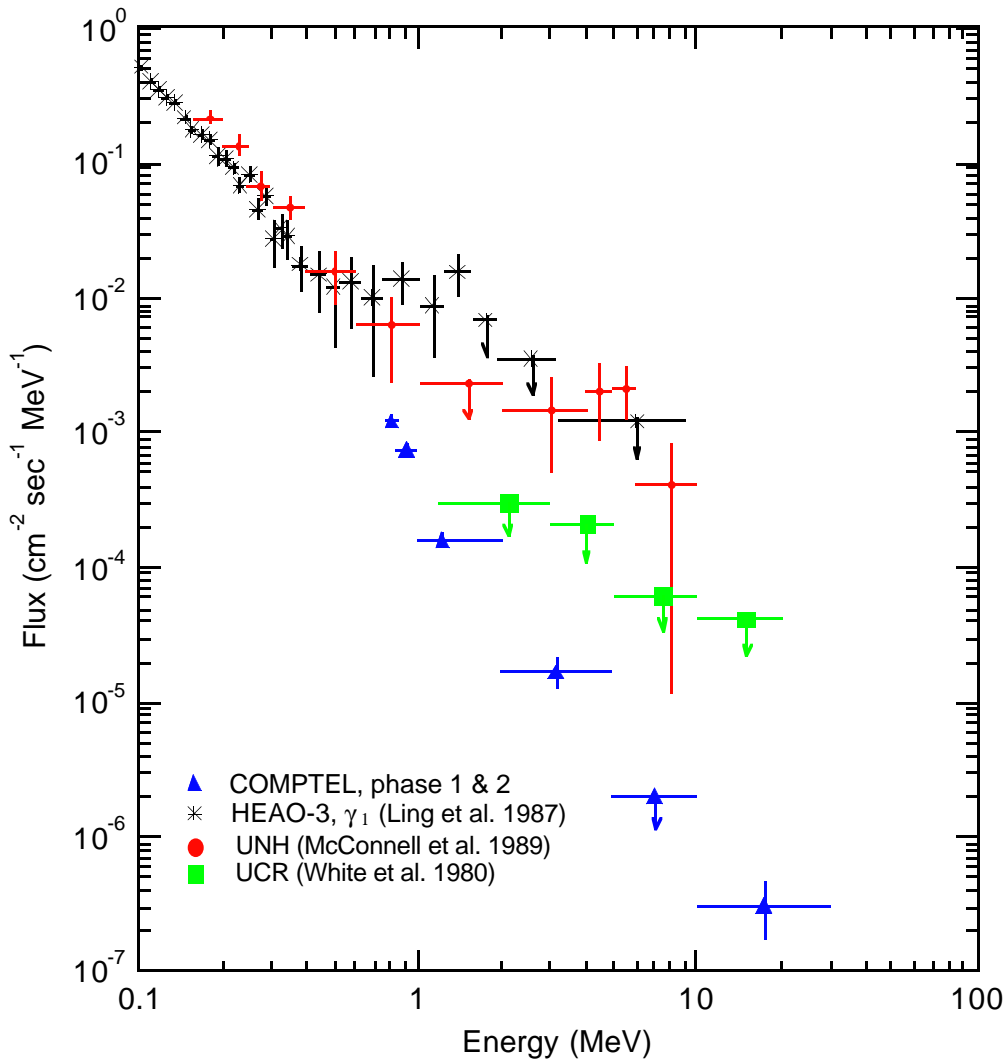


Fig. 2. The average spectrum of Cygnus X-1 observed by COMPTEL over the full seven weeks of observations obtained during phase 1 and phase 2 of the CGRO mission. For comparison, other representative observations are also shown.

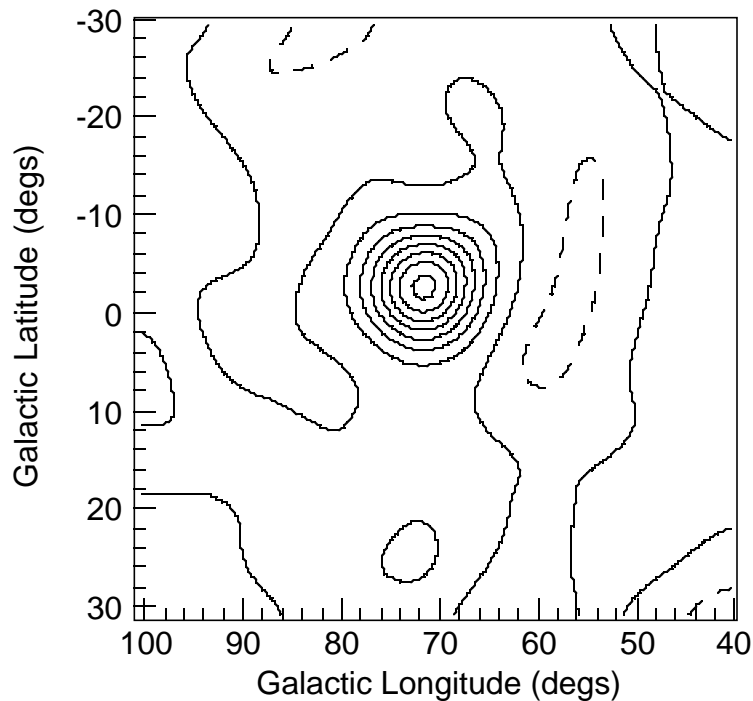


Fig. 3. Maximum likelihood image of the Cygnus region for the 0.75-1.0 MeV energy range derived from seven weeks of data collected during phase 1 and phase 2 of the CGRO mission. The response from Cygnus X-1 (at $l=71.3^\circ$, $b=3.1^\circ$) stands out clearly. (The likelihood contours start at a level of -30 with a stepsize of 15.)

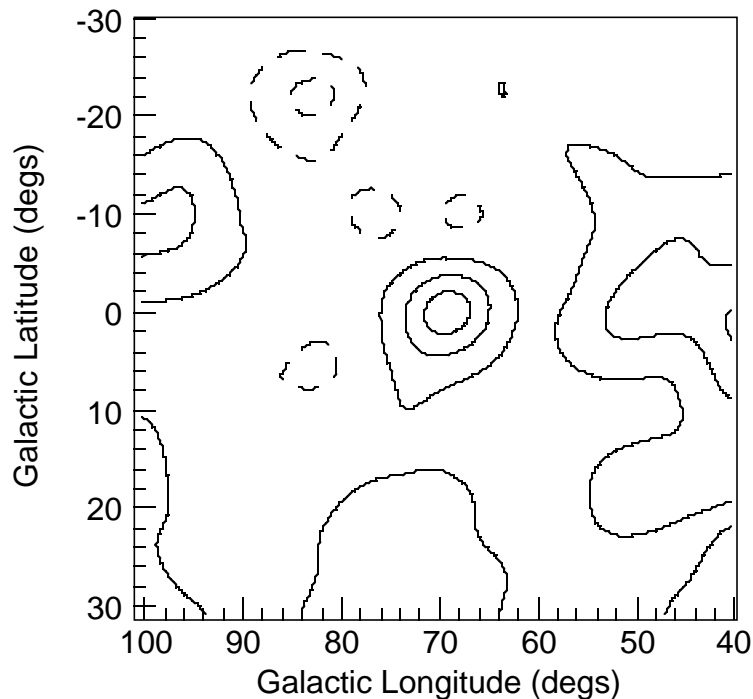


Fig. 4. Same as in Figure 3, but now for the energy interval 2.0-5.0 MeV. A response which is consistent with the location of Cygnus X-1 is still seen. The significance of this detection is at the 3.5σ level. (The likelihood contours start at a level of -30 with a stepsize of 8.)

DISCUSSION

We have now extended the measurement of the Cygnus X-1 spectrum up to energies beyond 2 MeV, as can be seen in Figure 2. Variability near 1 MeV on a time scale of weeks has been observed. This variability, at least to first order, appears to be correlated with the variability near 100 keV.

The electron plasma temperature which we derive for a Wien-type spectrum ($kT \sim 190$ keV) differs considerably from typical temperatures measured at hard X-ray energies ($kT \sim 60$ keV). This conflict would suggest that our standard picture of the Cygnus X-1 system needs to be revised. We suggest here two possible explanations which may serve to resolve this discrepancy in the kT measurements.

First, it should be noted that the standard spectral modeling of Cygnus X-1 (as well as many other accreting X-ray sources) is based on the Comptonization model of Sunyaev and Titarchuk (1980). Recent observations of Cygnus X-1 by both OSSE (Grabelsky et al. 1993) and SIGMA (Grebenev et al. 1993) have already suggested that this model is inadequate to explain the broad-band observations (i.e., from <100 keV up to 1 MeV). Typically, a two-temperature Comptonization model provides a better fit to the data. This has led some to conclude that the underlying assumptions of the analytical Sunyaev-Titarchuk model are not valid in the case of Cygnus X-1. For example, Grebenev et al. (1993) have used more detailed Monte Carlo modeling of the Comptonization process to fit the observed spectrum.

Second, recent modeling of the X-ray emission (Haardt et al. 1993) has suggested that any comprehensive model of Cygnus X-1 must include a component which represents the reflection of hard X-rays off a cooler optically-thick accretion disk. This is in direct analogy to the modeling of AGN spectra. Haardt et al. (1993) have employed such a model in their analysis of EXOSAT data to suggest that the hard X-ray emission comes predominantly from an accretion disk corona with a kT value in the 130-200 keV range. The reflection of this hard X-ray flux off the optically thick accretion disk leads to a distortion of the hard X-ray spectrum which can explain the measured values of ~ 60 keV. The very high energy threshold of COMPTEL (750 keV) would make it relatively immune to the effects of any reflected component. Indeed, it is interesting to note that the coronal temperature implied by the EXOSAT data is roughly similar to that suggested by the COMPTEL data.

SUMMARY

We have presented the latest results from seven weeks of COMPTEL observations of Cygnus X-1. These data represent the highest sensitivity measurement of the Cygnus X-1 spectrum extending into the MeV energy range. These data suggest that we must re-evaluate the long-standing models for the high energy spectrum of Cygnus X-1. Further data from COMPTEL are expected during phase 3 of the CGRO mission.

REFERENCES

- Baker, R.E., et al. 1973, *Nature Phys. Sci.*, 245, 18.
Bloemen, H., et al. 1993, *ApJS*, in press.
de Boer, H., et al. 1991, *Proc. 4th International Workshop on 'Data Analysis in Astronomy'*, Erice, Italy (Plenum Press).
Done, C., Mulchaey, J. S., Mushotzky, R. F., & Arnaud, K. A. 1992, *ApJ*, 395, 275.
Grabelsky, D. A., et al. 1993, in *Compton Gamma-Ray Observatory (AIP Conf. Proc. 280)*, eds. Friedlander et al. (New York: American Institute of Physics), p. 345.
Grebenev, S., et al. 1993, *A&AS*, 97, 281.
Haardt, F., Done, C., Matt, G., & Fabian, A. C. 1993, *ApJ*, 411, L95.
Ling, J. C., Mahoney, W. A., Wheaton, W. A., Jacobsen, A. S., & Kaluzienski, L. 1987, *ApJ*, 321, L117.
Ling, J.C., et al.. 1994, these proceedings.
McConnell, M. L., et al. 1989, *ApJ*, 343, 317.
McConnell, M. L., et al. 1993, in *Compton Gamma-Ray Observatory (AIP Conf. Proc. 280)*, eds. Friedlander et al. (New York: American Institute of Physics), p. 335.
McConnell, M. L., et al. 1994, *ApJ*, in press.
Schönfelder, V., et al. 1993, *ApJS*, 86, 629.
Sunyaev, R. A. & Titarchuk, L. G. 1980, *A&A*, 86, 121.
White, R. S., Dayton, B., Gibbons, R., Long, J. L., Zanusso, E. M., & Zych, A. D. 1980, *Nature*, 284, 608.