Gamma-Ray Spectra & Variability of Cygnus X-
Observed by BATSE

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Abstract

We present new BATSE earth occultation observations of the 25 keV–1.8 MeV spectrum and variability of Cygnus X-1 made between August 1993 and May 1994. We observed that the normal soft γ ray spectrum (γ_2) of Cygnus X-1 has two components: a Comptonized part seen below 300 keV, and a high-energy tail in the 0.3-2 MeV range. We interpret it in terms of a two-layer region, consisting of a high-energy core (with an equivalent electron temperature of ~210-250 keV) near the event horizon, embedded in a ~50 keV corona. In this scenario, the observed 25-300 keV photons were produced by Compton scattering of soft photons (~0.5 keV) by the hot electrons in the outer corona. These same hard x rays were further up-scattered by a population of energetic electrons in the inner core, producing the spectral tail above 300 keV. Cygnus X-1 went through an extended sequence of transitions between August 1993 and May 1994, when the 45-140 keV flux first decreased steadily from ~γ_2 to roughly one-quarter of its intensity over a period of ~140 days. The flux remained at this low level for about 40 days before returning swiftly (~20 days) to approximately the initial γ_2 level. During the transition, the spectrum evolved to a shape consistent with either a power law with photon index of ~2.6 or a single temperature Compton model with electron temperature $kT' = 110 \pm 11$ keV, and optical depth $\tau = 0.40 \pm 0.06$, and then returned essentially to the original γ_2 spectrum at the end of the active period. The overall cooling of the system during the low flux period may be due to an increase in the soft photon population which effectively quenched the hot electrons in these regions through Compton scattering.

Subject headings: Black Holes, Gamma Rays

1. Introduction

Cygnus X-1, the prototype black-hole (BH) system, 5.6 d binary, and one of the brightest soft gamma-ray (>25 keV) emitters (Liang & Nolan 1984; Ling 1988) in our galaxy, has been the subject of intense study for three decades. It is a highly variable source on time scales ranging from milliseconds to years, but its long-term secular variability remains poorly understood, not only theoretically, but even at the purely descriptive level. This is largely due to the lack of a body of uninterrupted and homogeneous observations spanning a reasonably wide range of energies. For some time we have been attempting to address this question by studying the available data, and by obtaining new observations relevant to Cygnus X-1 and to its connection with other possible BH candidates (Ling 1988, 1991). Previous and current observational results are briefly summarized below. Details of the new BATSE earth occultation observations are given in Section 2. Interpretations of the results are summarized in Section 3.

1 Previous Observations

From the beginning of the modern era with the "Uhuru" transition observed in 1971, to the launch of the Compton Gamma-Ray Observatory (CGRO) in 1991, at least two types of long-term variability have been identified, each accompanied by distinctive flux and spectral changes. Transitions in the 1-10 keV (which we hereafter term "soft") X-ray flux between the "low state" (LS) of about 0.35 of the Crab Nebula in the same range, and the "high state" (HS), have been observed in 1975 (Holt et al., 1979) and in 1980 (Ogawara et al. 1982). More recently, Cui et al. (1996) report the occurrence of a third LS/HS transition in 1996.

The Normal State. The LS has been observed repeatedly since 1971, both in soft and 45-140 keV (hereafter "hard") X-rays. Using 140 days of observations from HEAO 3 in 1979-1980, Ling et al. (1987) found the hard flux in the LS to be characterized as follows: (1) A broadly defined mean flux level of ~1.4 x 10^{-3} γ cm^{-2} s^{-1} keV^{-1} (called γ_2) which fluctuated between 1.2 and 1.6 x 10^{-3} with a time scale of days. This range of fluxes is generally consistent with the average levels of 1.3 x 10^{-3} and 1.4 x10^{-3} γ cm^{-2} s^{-1} keV^{-1} observed by HEAO 1 (Nolan et al 1981) in the spring and fall of 1978, respectively. (2) A characteristic spectrum in the 25-500 keV range (Sunyaev and Trumper 1979; Nolan et al. 1981; Ling et al. 1987; Salotti et al. 1992) that has been generally characterized as either a single temperature or two temperature Comptonization model (Sunyaev & Titarchuk 1980; Titarchuk 1994) with electron temperature kT~30-100 keV and optical depth τ ~ 3, or as an exponentially truncated power law (Philips et al. 1996). Above 500 keV, the shape of the spectrum has not been well established in the past due to limited statistics.

With the majority of observations of Cyg X-1 being similar, we have referred to this combination of LS and γ_2 the "normal state".

The LS/HS transitions. During the two observed transitions to the HS, the soft X-ray flux typically increased by a factor of 3-5, while the hard flux decreased (Dolan et al. 1977; Ling et al. 1983). The HS spectrum is softer than the LS/γ_2 spectrum below 100 keV; the two intersect near 10 keV. Such bi-state, anticorrelated spectral behavior has been explained in terms of Compton cooling of hot electrons by copious soft photons (Shapiro et al. 1976) or changes in the compactness parameter of the system (Kazanas 1986). Since the bolometric luminosity above 1 keV remained roughly constant during the LS to HS transition, Liang & Nolan (1984) suggested that such transitions are not necessarily due to changes in the accretion rate from the primary star, but may be caused by intrinsic instability in the accretion disk.

The 1979 γ_1 transition. In contrast to the LS/HS soft X-ray transitions, one major instance of low 45-140 keV hard X-ray flux has been observed from 1971-1991, in which the corresponding change in soft flux was small. This was in 1979 when HEAO-3 observed the hard ray flux at an unusually low level, of ~7.7×10^{-4} γ-cm^{-2}-s^{-1}-keV^{-1}, called the 'γ_1' level (Ling et al. 1983; 1987). From the beginning of the observation in the fall of 1979, the hard flux increased slowly towards the normal γ_2 level, but then proceeded on to reach an even higher level ('γ_3') where it stayed for about 20 days before finally settling down into what was apparently the normal LS/γ_2 state until the May 1980 LS/HS transition. During this entire hard X-ray excursion before the 1980 HS transition, the 3-6 keV fluxes measured by the Ariel 5 All Sky Monitor (Holt et al. 1979) stayed essentially at the LS level with weak evidence (2σ) for a possible correlated increase between γ_1 and γ_2 (Ling et al. 1987). The 1979 γ_1 spectrum was hard and complex, with a broad emission hump at ~1 MeV and a possible (~2σ) narrow 511 keV annihilation feature (Ling & Wheaton 1989), both suggestive of the presence of hot (~450 keV) pair plasma (Liang & Dermer 1988) in the system. Such high temperatures might result from a decrease in the number of the soft photons that usually cool the electrons by Comptonization processes. In any event, the (weak) correlation of soft and hard X-ray fluxes and heating are in strong contrast to the anticorrelation and cooling seen in the soft X-ray, LS/HS transitions.

Besides the above γ_1 spectrum, transient emission features above 500 keV have been reported by several groups, including Nolan et al. (1981) from HEAO-A4, and McConnell et al. (1989) from a balloon flight. However, the status of the high energy emission remain unsettled due to lack of confirmation from other experiments (Harris et al. 1993; Phlips et al. 1996). There was also no observation of major excursions from the normal LS/γ_2 state since the 1980 event and before continuous coverage was available with CGRO after April 1991. This included an extensive monitoring of the source by the Ginga All Sky Monitor (Kitamoto et al. 1996) from 1987 to 1991.

1.2 Current Observations

Since the launch of the CGRO on 5 April 1991, Cygnus X-1 has been monitored continuously by the Burst and Transient Source Experiment (BATSE) using the earth-occultation technique (Harmon et al. 1992; Paciesas et al. 1995; Ling et al. 1996b). Light curves and 16-channel spectra in the 25-1800 keV range with one-day time resolution are now available (Ling et al. 1996a; Paciesas et al. 1995) for ~1000 days covering the first three phases of the mission. Except for few short-term variations, Cygnus X-1 remained most of the time near the normal state during BATSE monitoring until the excursion reported here, which began in August 1993.

In this paper, we focus on the spectra and variability during the major transition observed between August 1993 and May 1994. Preliminary results of this event were reported by Paciesas et al (1995). Results of a more comprehensive study of the Phase 1-3 data are given in a separate paper (Ling et al. 1996a). During this ten-month period, Cygnus X-1 went through a sequence of hard X-ray transitions from the γ_2 level, through γ_1, to a new low level, γ_0, where it remained for about 40 days, before returning to γ_2. The γ_2 spectrum is consistent with previous observations with a hard x-ray Comptonized component <300 keV. However above 300 keV, we now clearly observe a high-energy tail, only hinted at in the HEAO 3 data, extending to ~2 MeV. We find the 1993 γ_1 spectrum to be clearly different from that observed in 1979, and softer than γ_2. As the hard X-ray fluxes changed, the spectrum evolved from the two-component shape for γ_2 to a softer spectrum consistent with either a power-law (photon index ~2.6) or a single-temperature Compton model (kT = 110 keV, τ = 0.4) for γ_0, before returning to approximately the same γ_2 shape at the end of this period.

2. Observations and Results

Results presented in this section were obtained using the JPL Enhanced Earth Occultation (EBOP), developed under the CGRO Guest Investigation Program. EBOP is an end-to-end system which starts with continuous (CONT) count data from the BATSE Large Area Detectors (LADs), and yields photon spectra and light curves for each cosmic source in a specified input catalog. EBOP consists of two major sections: an earth-occultation fit which extracts the cosmic source count rate and associated Poisson and systematic error estimates from the time series of CONT data, and a spectral analysis system which converts count rate estimates to a single physical flux estimate using the standard spectral analysis program XSPEC. Details of the EBOP system have been described by Ling et al. (1996b).

Figure 1-a shows the 45--140 keV light curve, with 1-day resolution, measured by BATSE between August 1993 and May 1994. Several major data gaps are due to periods of spacecraft orbit reboost (TJD 9264-9279, 9310-9314, & 9334-9341), and when the instrument changed its configuration (TJD 9401-9418). As shown in Figure 1-a, the hard X-ray flux decreased gradually over 140 days from approximately the normal γ_2 level (Ling et al. 1987) to a very low flux level γ_0 (Paciesas et al. 1995), roughly one-quarter of the γ_2 level. The flux remained at the γ_0 level for about 40 days before returning swiftly (~20 days) to γ_2, where it remained until at least the end of May 1994.

Figures 1:b1-b4 shows average spectra observed in four different intervals during this period. These include the two periods when the source was approximately at the γ_2 level, at the start (TJD $)2.? 6--9250; TJD = JD - 2440000.5) and the end (TJD 9448 --949S) of the transition series, and two periods between, γ_1 (TJD 9308--9347) and γ_0 (TJD 9356--9397). The spectral deconvolution for converting the daily source count rates to photon fluxes, was done with XSPEC using a single-temperature Comptonized model (Titarchuk 1994) (solid lines in Figure 1-b). Data included in each fit consist of average count rates in 14 energy channels measured typically by 2 to 4 detectors exposed to the source for a given viewing period, and several viewing periods in each of the four selected intervals. Other models such as the power law and two temperature Comptonized model were also used to fit the data. Table 1 summarizes all the fit results. None of the three models tried provided acceptable fits to the two γ_2 spectra (Figures 1-b1 & b4) which may be qualitatively described as having two components, a Comptonized shape in the 25-300 keV region, and a power law tail, $F = AE^{-\alpha}$ from 300 keV to ~1 MeV with photon power law indices α ~2.4 and α ~2.8, respectively. The high energy fluxes are generally consistent with the 0.8--2 MeV fluxes measured by COMPTEL (shown as * in Figures 1-b1 & b4; McConnell et al. 1994) in August of 1991, when the source was in the normal LS/γ_2 state.

As the source evolved from γ_2 to γ_1 (Figure 1-b2) and then to γ_0 (Figure 1-b3), the overall spectrum softened. The spectrum observed by BATSE at γ_1 can be best fitted with a single-temperature Comptonized model with kT = 106.5 (-1 40.(), -27.6) keV, and τ = 1 .(K) (+0.46, -0.36). This is markedly different than that observed in 1979 by HEAO-3 (Ling et al. 1987) which showed a broad spectral feature centered at ~1 MeV superposed on Comptonized spectrum with kT = 73 (+ 1'7,-1 1) keV and τ = 1.67 (+0.20, -0.24). BATSE data show clearly that γ_1 is not a unique 'State.' in the sense of a characteristic condition to which the source repeatedly returns. The difference shown in the 1979 and 1993 γ_1 spectra was first pointed out by Paciesas et al. (1995). It is likely that in time periods, the source merely passed through the same flux level, but was driven by very different physical processes in the system. The γ_0 spectrum can be fitted well with either a single temperature analytical Compton model [solid line kT : 1-/0 (-t 200, -66 keV), τ = ().25 (-1 0.40, -0.25)] or a power law (photon index = 2..S7) with χ^2/ν= 1,2.3 (ν=165) and 1.27 (ν: 1 66), respectively. Single-parameter uncertainties were estimated at the 1σ level, for models which gave acceptable fits only, according to the method of Avni (1976).

Cygnus X-1 was also observed by the Oriented Scintillation Spectroscopy Experiment (OSSE) (Phlips et al. 1996) on February 1--8 (TJD 9384--9391, VP-318.1) and May 24--25 (TJD 9496- -949-/, VP-328) 1994 when the source was in the γ_0 and near γ_2 level, respectively (see Figure 2). A direct comparison of all other OSSE and BATSE's spectra obtained during the Phases 1-3 of the CGRO mission, is given in a separate paper (Ling et al. 1996a). Briefly, for VP's 318.1 and 328, changes in the overall flux level and spectral shape between γ_0 and γ_2, similar to those seen by BATSE, have also been observed by OSSE. There are some apparent systematic differences in the normalization, but the spectral shapes generally agree well. For VP-318.1, a power-law spectral shape was observed by both OSSE and BATSE. The best-fit photon index for OSSE is α = 2.72± ().03 (Phlips et al 1996), which is consistent with BATSE's α = 2."/ ± 0.2. OSSE fluxes, however, were generally lower than BATSE's, by about 25% at 100 keV. For VP-328, both BATSE and OSSE spectra show consistent flux and (!c)Iilll tcjIj-like. spectral shape. The OSSE flux at 100" keV is estimated to be ~5% lower than BATSE's.

3. Discussion

Problems with the Analytic Comptonization Model, Because standard analytic Comptonization models fail to give adequate fits to the two γ_2 spectra, we have sought others which are conceptually simple and physically sensible. It is important to recognize that there are serious shortcomings of the analytical Comptonization model which has been frequently used in the past for characterizing Cygnus X-1 spectra without questioning its applicability as well as reliability of the results. First, for a 2-temperature model, any likely coupling between the two regions is totally ignored, which is physically implausible. Also, the analytical formula for the Comptonization spectrum is valid only within a region in the parameter space (β, kT_e) defined by Figure "/ in Hua & Titarchuk (1995), where β is a function of optical depth τ (Titarchuk 1994). As indicated in the previous section, only two of the four spectra (see Table 1), namely γ_1 and γ_0, can be best-fitted with a single-temperature Comptonization model. The corresponding β values for these two spectra based on the best-fit parameters are ().61 and 1.81, respectively. For the γ_1

spectrum, the point determined by the coordinates (β, kT_e), or *(0.61, 1(16. S)* is within the region where analytical formula is applicable. "This is not true, however, of the γ_0 spectrum, for which the coordinate point (1,81, 170 keV) is on the. boundary of" the region. The problem is more serious for the lower limit of the γ_0 fitting, which has coordinates (infinite, 372.9 keV), far outside Of the region. Thus the best-fit parameters derived from the analytical Compton model cannot be considered reliable for characterizing the condition of the source at the γ_0 level. Hua & Titarchuk (1995) have conducted an extensive comparison of results produced by the analytical and Monte Carlo Comptonization methods, and have shown that many of the weaknesses and restrictions shown in the analytical model have been eliminated with the Monte Carlo method. For these reasons we have adopted the. Monte Carlo Comptonization code developed by Hua & Titarchuk (199S), which we believe is a superior method for modeling the conditions of the source represented by the four spectra shown in Figure 2. Table 2 lists the corresponding fluxes for each of the four spectra shown in Figure 2 which we used for our Monte Carlo study.

Monte Carlo Core/Coronn Model. The two-region Monte Carlo model shown in Figure 2 offers a physically attractive picture for interpreting the γ_2 spectra. Such a configuration is similar to one proposed recently by Skibo and Dermer (1996). It consists of a high temperature 'core' embedded in a cooler 'corona'. For simplicity, spherical symmetry equal electron densities in core and corona have. been assumed. As inputs to the model fit, we. used 0.5 keV soft source photons, which were fed radially into the system at the outer surface of the corona. Note that the proposed geometry is only one possible configuration which has been extensively studied to date under this investigation. Other geometrical configurations for both the hot Comptonization region as well as the. incident soft photon source cannot be ruled out at the present.

The corona/core model is described by four parameters, the temperature kT_1 and optical depth τ_1 of the corona, and of the core, kT_2 and τ_2. The best-fit results for the two γ_2 spectra are shown as dashed lines in Figures 1-b1 & b4 and listed in Table 1. Our study shows that the low-energy component (<300 keV) of the γ_2 spectrum is primarily due to Compton up-scattering of the incident soft photons in the corona, with kT ~48 keV and τ --1.3, The high-energy (>300 keV) component, however, mainly results from further Compton scattering in the core of hard X-rays produced in the corona. If the electrons in the core are thermal, their average kT is --2.30 keV and τ -- 0.4. We have also modeled the four spectra using the Monte Carlo code for a single-temperature region (see Table 1). We find that the, single-temperature Monte Carlo Compton model (dashed line in Figure 1. b3) fits the γ_0 spectrum very well (kT = 110 ± 11 keV and τ = 0.4 ± 0.6), but poorly, as expected, for the two γ_2 spectra (χ^2/ν ~2.55, 2.72 for ν=11). The best-fit parameters for the γ_0 spectrum are consistent with those obtained using the analytical model.

However, the parameter space derived from the Monte Carlo method seems to be better conditioned or more tightly confined than that derived from the analytical model. This demonstrates another fundamental difference in the lc.suits produced by the two models. The best-flt parameters for the. γ_1 spectrum (kT = 1 15 ± 8 keV, τ = 0.7 ± 0.06; dashed line in Figure 1 -b?) are also consistent with those derived from the analytical model [kT =106.5 (-1 40.0, -27.6), τ = 1,(1 (-1 ().46, -0.36)]. The fit, however, is not as good (χ^2/ν ~2.1 for v= 1 1). By excluding channel 1 from the model fit, the χ^2/ν improves to 0.7. Errors shown for they] and γ_0 parameters derived from the Monte Carlo model fit were estimated using the method prescribed by Avni (19"/6). Corresponding errors for the two-temperature core/corona model are more difficult to assess as they have to be determined from a foul- dimensional hyperspace (Iwo temperature and two Optical depth parameters) mapped with results obtained from a large number of Monte Carlo computations.

Results of our Monte Carlo study can be summarized as follows: (1) A model of soft photons with characteristic black-bed y temperature of ().S keV, which are radially fed into a two-temperature core/corona system described above seems to describe the. two γ_2 spectra well. (2.) As the source evolved from γ_2 to γ_0, the system changed from two-temperature to a single-temperature region with kT - 110 keV and τ ~0.4. The apparent ceding of the cwc.rail system is consistent with the disappearance of the outer corona while the core temperature dropped from ~230 keV to ~110 keV, and the optical depth remained unchanged. As discussed in Section 1, the decrease in hard X-ray luminosity coupled with an overall cooling of the system, are gene.1 ally expected in a soft X-lay LS to 1 IS transition such as that observed by Hakucho (Ogawara et al. 1982) and 1111A()- 3 (Ling et al. 1983) in 1980. They are also consistent with the temporal and spectral variability observed by BATSE for the 1996 1,S to 11S transition (Zhang, private communication).

In this core/corona model, we have assumed the core to be described by a thermal electron population of temperature kT_1. Its true nature, however, could include both thermal and nonthermal components. Chakrabarti and Titarchuk (1995) recently proposed that relativistic electrons with energies up to 1 MeV may be associated with the free infalling matter onto the black hole in the 'converging flow' region near the event horizon (1 to a few R_{rms}). They further predicted that during an X-ray LS to HS transition, a continuum of soft photons produced in the outer disk could be up-scattered directly by high energy electrons in the 'converging' region, changing the spectrum from the. standard Comptonized shape to a power-law with photon index of ~2.5 for t}]c.11S. This scenario is generally consistent with the evidence presented here.

In summary, our main results are as follows:

1. We have observed and characterized the 'normal state' soft gamma-ray spectrum as having two components, a Comptonized shape below 300 and a spectral tail extended from ~300 keV to ~1 MeV. The latter is consistent with that observed by the COMPTEL experiment (McConnell et al. 1994).

2. We interpreted the normal LS/γ_2 spectrum in terms of a simple 2-temperature core/corona model, using the Monte Carlo calculation to demonstrate that the emergent spectra agree well with the observed data.

3. Cygnus X-1 went through an extended transition between August 1993 and May 1994, the first observed since the 1979-1980 event observed by HEAO-3 (Ling et al, 1987). Over a period of ~300 days, the hard x-ray flux (45-140 keV) decreased slowly (~140 days) from γ_2, through γ_1, to a new low level γ_0 one-quarter of γ_2, before returning to γ_2.

4. The γ_1 spectrum showed a very different shape than that observed by HEAO-3 in 1979 (Ling et al 1983 and Ling et al 1987). Thus the γ_1 level of the 45-140 keV flux cannot be considered as the signature of any single unique "state" of the system.

5. The low-flux γ_0 spectrum had a softer power law form. Our Monte Carlo modeling of the spectrum suggests a general cooling had occurred in the system.

We hope that these results will stimulate an interest in more extensive investigations, both theoretical and observational, in the future.

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Table 1. Cygnus X-1 Model-lit Parameters

Power-law Model				
TJD	9226 -92S0	9308-9347	9356-9397	9448-9495
Flux-Level	(γ_2)	(γ_1)	(γ_0)	(γ_2)
photon index	2.20	2?94 0.02	2.57 ± 0.04	2.09
χ^2/ν (v)	13.7 (82)	1.61 (180)	1.27 (166)	8.5 (138)

Compton Analytical Model Parameters		Single-Component Compton Model			Two-Component Compton Model	
TJD	9226-9250	9308-9347	93 S6-9397	9448 -949s	9226-9250	9448 -949s
Flux-Level	(γ_2)	(γ_1)	(Ye)	(72)	(72)	(72)
kT_1 (keV)	53.1	$106.5^{+400}_{-27.6}$	169.9^{+203}_{-66}	55.7	40.4	51.7
τ_1	2.68	$1.00^{+a46}_{-0.36}$	$0.250^{+0.040}_{-0.25}$	2.73	3.36	2.91
kT_2 (keV)					440	260.1
τ_2					0,39	154.7
χ^2/ν (v)	4.3 (81)	1.?3 (179)	1.?3 (1.55)	284 (13-/)	4.2? (/8)	258 (134)

Compton Monte Carlo Model Parameters		Single-Temperature Corona Model			Two-layer Corona/Core Model	
TJD	9226 -92S0	9308-9347	93 S6-9397	9448 -949S	9226-9250	9448-9495
Flux-Level	(γ_2)	(γ_1)	(70)	(72)	(γ_2)	(72)
kT_1 (Outer Corona)	80	111.6 ± 8.0	107.7 i 11.0	85	48	48
τ_1	1.35	0.723 ± 0,0s5	0.435 ± 0.060	1.40	1.30	1.35
kT_2 (Inner Core)					210	250
τ_2					0.40	0.40
χ^2/ν (v)	755(11)	1.98 (11)	0.18(11)	272(11)	1.23 (9)	1.35 (9)

Table 2. Cygnus X-1 Fluxes

Energy (keV)		FLUX (photons/cm²-s-keV) x 10^{-6}			
TJ[)		9226-9250	9308.9347	93 S6-9397	9448-9495
Flux-Level		(γ_2)	(γ_1)	(γ_0)	(γ_2)
24	31	9230 ± 164	7852 ± 282	4541 ± 191	8959 ± 13S
31	41	5669 ± 66	37064101	2351 ± 69	5663 ± 62
41	55	3449 ± 34	2104 ± 54	1189 ± 36	3504435
55	73	1988 ± 20	1178430	566.2 ± 19.7	2075420
73	98	1174 ± 13	665.9 ± 16.5	277.8 ± 12 9	1233 ± 13
98	123	675.5 ± 9,0	376,7 ± 11.2	137.2 ± 9.0	733,43 8.7
123	162	373.4 ± 6.0	201.747.5	69.1 ± 5.8	424.5 ± 5.8
16?	230	158.7 ± 3.6	87.7 ± 4.3	30.9 ± 3.7	184.4 ± 3.9
230	313	57.5 ± 2.7	34.4 ± 3.4	9.12 ± 3.04	68.3 ± 2.9
313	429	?0.1 ± 2.0	12.2 ± 2.6	3.614 2.30	24.74 ? 1
429	595	5.89 ± 1.73	3.14 ± ?,62	-1.03 ± 2.44	8.16 ± 201
595	766	2.284 1.05	2.47 ± 2.00	0.756 ± 1,909	3.13 ± 1.42
766	1104	1.5640.93	0,765 ± 1,373	0.7014 1,619	2.47 ± 1.1?
1104	1-/00	-0.241 ± 0.393	-0.715 ± 0.998	-0,3924 1.144	0.681 ± 0.553

References:

Avni, Y., Ap. J., 210, *642 (1976).*

Chakrabarti S.K. and Titarchuk, 1.., Ap.J .455, 623 (1995).

Cui, W., W. A. Heindl, R. E. Rothschild, S. N. Zhang, K. Jahoda and W. Focke, accepted for publication in the ApJ (Letters), (1996)

Dolan, J. F., Crannell, C. J., Dennis, B. R., Frost, K. J., and (h-wig, 1,. 11., Nature, 267, 5615 (1977).

1 Jarmon et al, The Compton Observatory Science Workshop, NASA CP3 137, cd, by C. R. Shrader, N. Gehrels, B. Dennis, *69 (1 992)*

Harris, M. J., Share, G. H., Leising, M. D., and Grove, J. E., Ap. J., 416, 601 (1993).

Holt, S. S., Kaluzicnsky, L. J., Boldt, E. A., and Serlemitsos, P. J., Ap. J., 233, 355 (1979).

Hua, X.-M, and Titarchuk, I.., ApJ, 449, 188, (1995)

Kazanas, D., Astron. Astrophys. 166, 1.19 (1986).

Kitamoto, S., W. Egoshi, S. Miyamoto, H. Tsunemi, J, C. Ling and Wm. A. Wheaton, submitted to Ap. J. (1996).

Liang, E. P., and Dermer, C. D., Ap. J., 325, L39 (1988).

Liang, E. 1'., and Nolan, 1'., Space Sce. Rev., 38, 353 (1984)

Ling, J. C., W. A. Mahoney, W. A, Wheaton, and A. S. Jacobson, Ap. J., 275, 307 (1983).

Ling, J. C., W. A. Mahoney, W. A. Wheaton and A. S. Jacobson, Ap. J. (Letters), 32.1, 1.117 *(1987),*

Ling, J. C., Astrophysical Sources Workshop Proceedings, (New York: AIP 170), 315 (1988).

Ling, J. C. and Wm. A. Wheaton, Ap.J. (Letters), 343, 1.57 (1989).

Ling, J. C., Gamma-Ray Line Astrophysics, ed Ph. Durouchoux and N. Prantzos, AIP *?.32, 407, 199],*

Ling, J. C., et al., to be submitted to ApJ, (1996a).

Ling, J. C., Wm A. Wheaton, W. A. Mahoney, R. T. Skelton, R. G. Radocinski, and 1'. Wallyn, to be published in the. Astronomy. & Astrophysics (1996b)

McConnell, M. L., Forrest, D. J., Owens, A., Dunphy, R. P., Vestrand, W. T., and Chupp, E. L., Ap. J., 343, 317 (1989).

McConnell, M., L. et al., Ap. J. 424,933 (1994).

Nolan, P:. L. et al., Nature, 293, 275 (1981).

Ogawara, Y. et al., Nature, 295, 675 (1982).

Paciesas, W. S. et al., Proc. NATO Advanced Study Institute Conf., Les Houches, ed. M. Signore (Kluwer, The Netherlands) (1994).

Philips, *11.1'.* et al., Ap. J. 465, 907 (1996).

Salotti, 1,. et al., Astron. & Astrophys. 253, 145 (1992).

Shapiro, S. 1... Lightman, A. P., and Eardley, D. M., Ap. J., 204, 187 (1976).

Skibo, J.G. and Dermer, C.D., Ap. J. 455, 1.25 (1995).

Sunyaev, R. A., and Titarchuk, L. G., Astron. Astrophys., 86, 121 (1980).

Sunyaev, R. A., and Trumper, J., Nature, 279, 507 (1979).

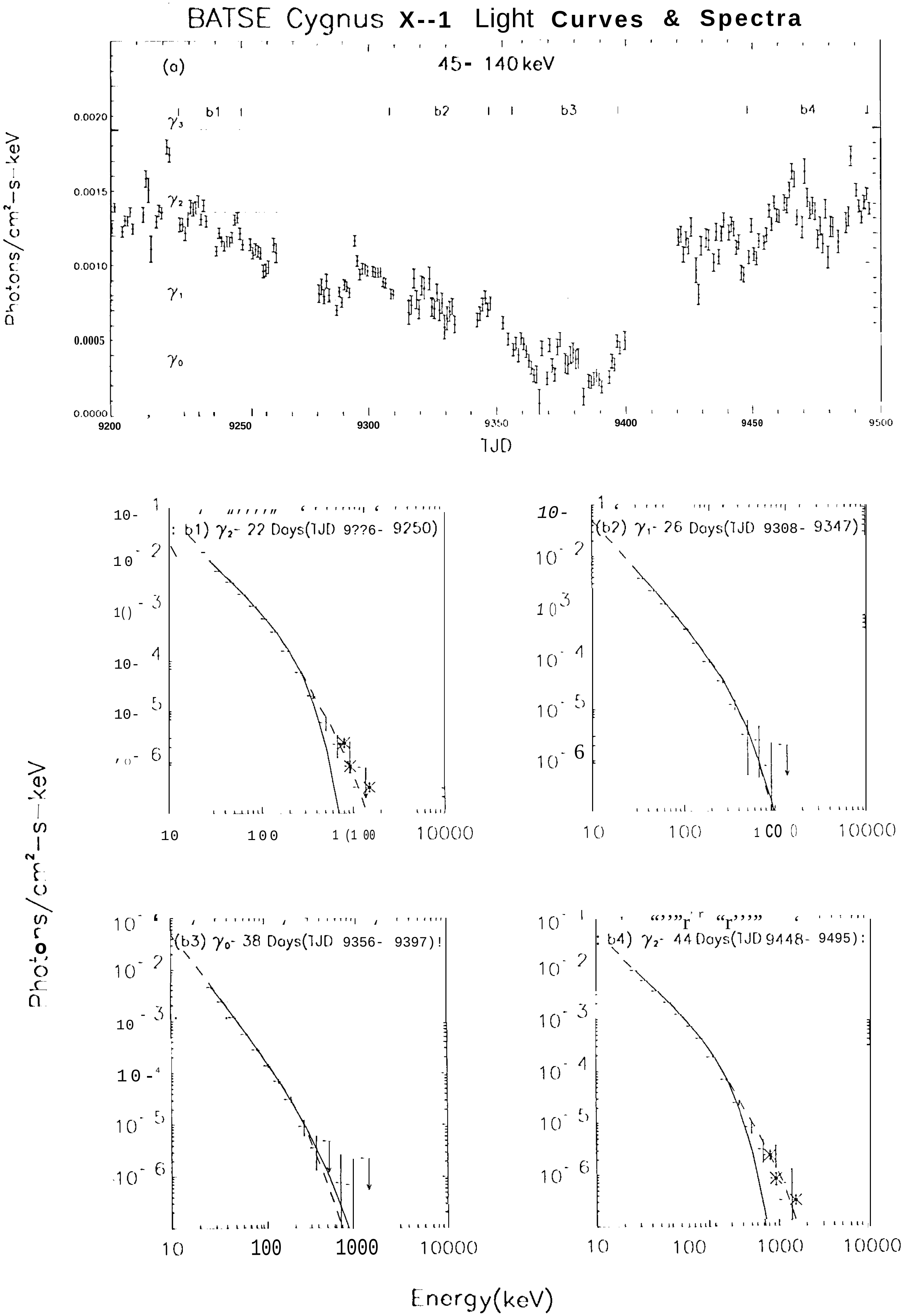
Titarchuk, L., Ap.J., 434, 570 (1994)

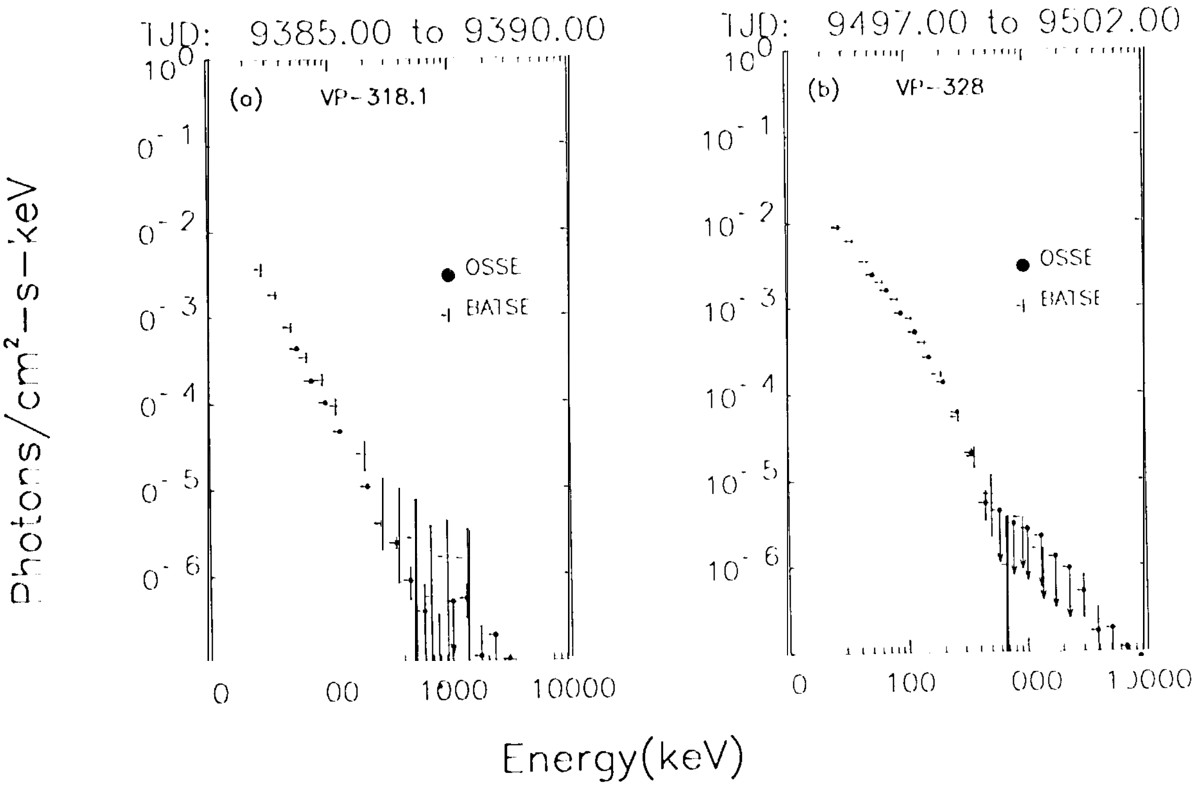
Figure Captions

Figure 1. (a) The first complete gamma-ray transition of Cygnus X-J, of-300 days duration, was observed by BATSE between August 1993 and May 1994 as indicated by the lightcurve of the 45-140 keV fluxes. The solid lines represent four typical flux levels. Three of these levels (γ_1, γ_2 and γ_3) were seen by HEAO-3 in 1979-1980, and the fourth (y_0) is a new level seen for the first time by BATSE (Paciesas et al, 1995). (b) The γ_2 spectra (b1 & b4) consist of two-components: a high-energy tail above 300 keV superposed on the Comptonized component below 300 keV. As the hard X-ray flux decreased from γ_2 to y_0, the spectrum evolved to a shape consistent with either a power-law with spectral index of ~2.6, or a single-temperature Compton model (panel-b3). The solid line in each panel represents the best-fit single-temperature analytical Compton model and the dashed line represents the best-fit produced by Monte Carlo simulations of the system. Fluxes measured by the COMPTEL experiment (McConnell et al, 1994) in August 1991 (*) are also included in panels-b1 & b4 for comparison.

Figure 2. Simultaneous observations of Cygnus X-1 were made by BATSE and OSSE during VP-318.1 and VP-328 of the mission when the source was in the γ_0 and ~γ_2 level, respectively. Two contrasting, spectral shapes were observed by both experiment below 500 keV: a power-law for VP-318.1 compared to a Comptonized shape for VP-328.

Figure 3 A two-layer system consisting of a inner high-energy core embedded in an outer corona is used as the model for detailed Monte Carlo simulations of two γ_2 spectra. Results of these simulations are summarized in Table 1.


BATSE Cygnus X--1 Light Curves & Spectra
(a)
45- 140 keV
b1
b2
b3
b4
γ_3
γ_2
γ_1
γ_0
Photons/cm²-s-keV
TJD
(b1) γ_2- 22 Days(TJD 9226- 9250)
(b2) γ_1- 26 Days(TJD 9308- 9347)
(b3) γ_0- 38 Days(TJD 9356- 9397)
(b4) γ_2- 44 Days(TJD 9448- 9495)
Energy(keV)


TJD: 9385.00 to 9390.00
(a) VP-318.1
OSSE
BATSE
TJD: 9497.00 to 9502.00
(b) VP-328
OSSE
BATSE
Photons/cm²-s-keV
Energy(keV)

Cygnus X-1 System- Monte Carlo Simulation