A Review of Cygnus X-1 Soft γ-ray Observations

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Abstract. Since the first discovery of Cygnus X-1 in the mid 1960's, the source has been the subject of intense soft γ-ray (30 keV – 10 MeV) observations by many balloon and satellite experiments. A large body of spectral and temporal information about the source has been gathered to date. While these results have significantly enhanced our understanding of the Cygnus X-1 system, they have also raised new questions that need to be addressed by future missions. This paper provides a brief summary of some of the important long-term temporal and spectral results obtained over the last thirty years, and discusses the current status and issues that need to be addressed by upcoming missions.

1. INTRODUCTION

Cygnus X-1 is one of the brightest soft γ-ray sources in our Galaxy. For more than thirty years since the source was first discovered in the mid 1960's[1], it has been observed by numerous balloon[2-4] and satellite experiments. The latter include OSO-7[5], OSO-8[6], HEAO-1[7], HEAO-3[8-9], SMM[10], SIGMA[11], OSSE[12], BATSE[13-15], COMPTEL[16-17], ROSSI[18] and BEPPOSAX[19]. This paper gives a brief summary of the long-term spectral and temporal behavior of the source. Specific emphasis is given to the description of three distinct soft γ-ray spectra that were observed when the source was in the standard state (Section 2), high x-ray state (Section 3) and superlow x-ray/high γ-ray state (Section 4), respectively. Important issues that need to be addressed by future missions is also discussed.

2. THE STANDARD STATE

Cygnus X-1 is highly variable with time scale ranging from milliseconds to years. The source stayed most of the time in its standard state, known also as the x-ray "low/hard" state. Under this condition, the soft γ-ray spectrum can be generally described as having two components: a Comptonized[20] shape up to ~300-400 keV with an electron temperature of kT ~30 - 100 keV and optical depth of $\tau_s \sim$ 1-3[2,7,8,9,11] and a high energy power-law tail extending from 0.4 to several MeV[12,13,16]. Figure 1 (left panel) shows a composite broadband spectrum measured contemporaneously by COMPTEL, BATSE and OSSE during the first three cycles of the CGRO mission in 1991-1994[10]. The best-fit power-law index of the high energy component (> 0.6

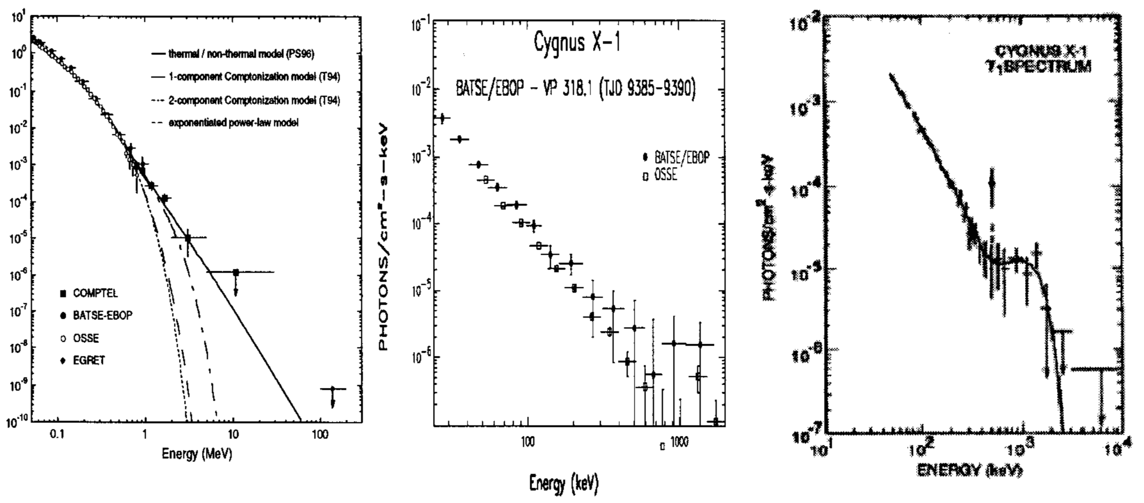

Figure 1. Three very different soft γ-ray spectra associated with the Cygnus X-1 states were observed in the past three decades: *Left Panel:* the standard-state spectrum observed by COMPTEL, BATSE and OSSE in 1991-1994[16] consists of two components: a Comptonized shape below 400 keV followed by a power-law tail extended to ~5 MeV with an index of ~3.3. *Middle Panel-* the high X-ray state spectrum observed by BATSE[13] and OSSE[12] in 1994 is power-law like with photon index of ~2.7. *Right Panel:*: the superlow X-ray /high γ-ray state spectrum measured by HEAO-3 in 1979 consists of a Comptonized component below 0.4 MeV, a broad γ-ray Gaussian feature (0.4-1.5 MeV) centered at 1 MeV[9] and a weak (~2σ) narrow 511 keV feature[34].

MeV) measured by COMPTEL[10] is ~3.3. The luminosity in the 0.02 - 0.2 MeV, 0.2 - 1 MeV and >1 MeV bands was estimated[21] to be 20.5, 4.8 and 0.6 x 10^{36} erg/s, respectively, with ~80% in the 20 - 200 keV band, assuming a source distance of 2.5 kpc.

The two-component standard spectrum may be interpreted in terms of a thermal model consisting of two interacting regions: a high-temperature core embedded in a lower temperature corona[13,22]. Such a model is qualitatively consistent with the advective accreting model[23], which is quasi-spherical and has a temperature gradient along the radius. The spectrum could also be interpreted in terms of a nonthermal model[24] of free infalling matter onto the BH in the converging flow region. More recently, a hybrid thermal/non-thermal model[25] has been shown to fit both the standard (low-state) spectrum[16] and the high x-ray state spectrum[17] well.

Electron-positron pairs could also exist in such a BH system and produce an annihilation feature[35]. HEAO-1[36] observed a broad feature centered at 500 keV with a flux of 5 x 10^{-3} photons/cm^2-s in 1977-1978 when the source was in the standard state. However, this was not seen in the γ_2, or the standard state, spectrum measured by HEAO-3 in 1979-1980, which set a 3σ upper limit of 4 x 10^{-3} photons/cm^2-sec for a broad feature[9] and 1 x 10^{-4} photons/cm^2-sec for a narrow feature[34]. More recently, OSSE[12] also placed an upper limit of 7 x 10^{-5} photons/cm^2-sec for a narrow 511 keV line and 2 x 10^{-4} photons/cm^2-sec for a broad 511 keV line when the source was in its standard state.

3. THE HIGH X-RAY STATE

While Cygnus X-1 stayed most of the time in the standard (low) state, it is also known to make an occasional transition to a high (intensity) x-ray state. Such a transition has been seen at least five times in the last thirty years: in 1970 by Uhuru[26], in 1975 by Ariel 5 All Sky Monitor[27-28] and OSO-8[6], in 1980 by Hakucho[29] and HEAO-3[8-9], in 1994 by BATSE[13], and in 1996 by ROSSI[18], BATSE[15], and COMPTEL/OSSE/BATSE[17]. During a typical standard state to high state transition, the 1-10 keV flux increased significantly, while the flux above 10 keV decreased in an anti-correlated fashion, with the spectrum pivoting at around 10 keV[15,30]. The overall soft γ-ray spectrum (>30 keV), however, evolved from the two-component shape (Comptonized + power-law tail) described above to a power-law with index of 2.6-2.7. Such spectral change was seen by both BATSE[13] and OSSE[12] for the 1994 event (see Figure 1, the middle panel), and by COMPTEL/OSSE/BATSE[17] for the 1996 event. It is important to note that in contrast to the softening of the spectrum below 200 keV, the high-state spectrum above 200 keV is actually harder than the standard (low) state spectrum. This is indicated by the power-law spectral index of 2.6-2.7 for the former and 3.3 for the latter. The standard and high x-ray state spectra were shown to intersect at ~1 MeV[17] in addition to that seen at ~10 keV[15].

4. THE SUPERLOW X-RAY/HIGH γ-RAY STATE

HEAO-3 γ-Ray Spectrometer[31] and Ariel 5 All Sky Monitor[27-28] discovered a new low x-ray state in 1979 which was called the "superlow" x-ray state[8-9]. Several unique features associated with this state are:

• Both the soft x-ray (3-6 keV) and hard x-ray (45-140 keV) fluxes were simultaneously low by at least a factor of two compared to those of the standard state, During the recovery phase from the superlow to the standard (low) state, the soft and hard X-ray fluxes tracked each other in a correlated fashion (Figure 2: left half of the figure), in contrast to the anti-correlation seen in a typical standard (low) to high x-ray state transition (e.g. see Figure 2: right half of the figure). The superlow-state spectrum and fluxes in the 50-200 keV range observed by HEAO-3 were independently confirmed by a contemporaneous balloon observation in 1979[3].

• From the standard state to the superlow state, a large fraction of the luminosity below 0.4 MeV was converted to energy above 0.4 MeV, showing a new type of anti-correlation between x rays and γ Rays[9]. The luminosity in the 0.05 – 0.4 MeV and 0.4-1.5 MeV bands are 10.5 and 13.8 x 10^{36} ergs/s, respectively, for the superlow state compared to 17.0 and 0.85 x 10^{36} erg/s for the standard (low) state[9]. Because the γ-ray (0.4 –1.5 MeV) luminosity increased by more than an order of magnitude, the superlow x-ray state could also be considered a high γ-ray state.

• The superlow state spectrum, which was also called the γ_1 spectrum[9] (see Figure 1 right panel), consists of a Comptonized component below 0.4 MeV and a broad

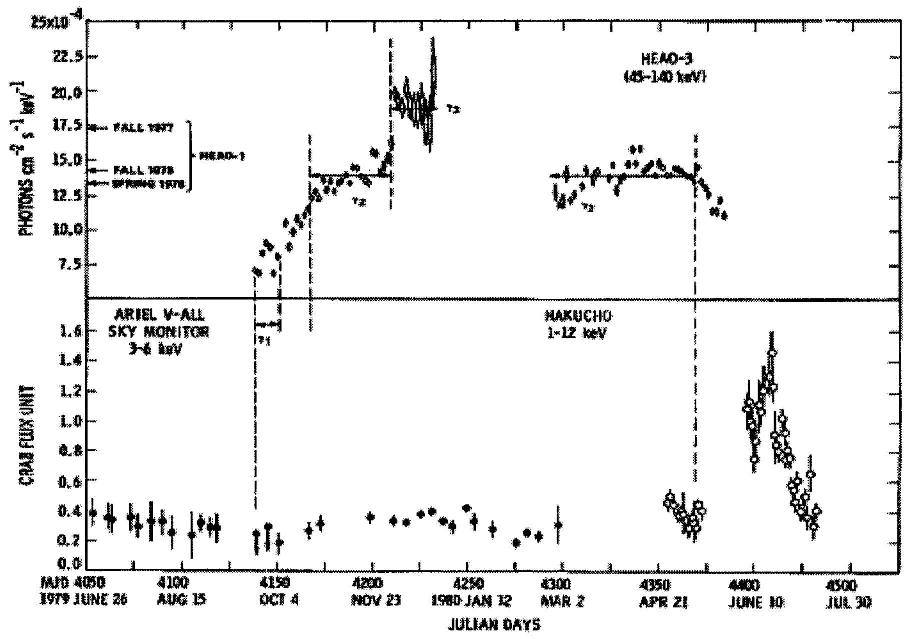

Figure 2. Two contrasting transitions were seen by HEAO-3 (45-140 keV), Ariel V All Sky Monitor (3-6 keV) and Hakucho (1-12 keV) experiments in 1979-1980[8-9]. During the 1979 superlow x-ray state to standard state transition (left half of Fig 2), the soft and hard x-ray fluxes measured by Ariel V and HEAO-3 tracked one another in a correlated fashion. This is in contrast to the standard state to high x-ray state transition seen in 1980 when the soft and hard x-ray fluxes, provided by near contemporaneous data of HAKUCHO and HEAO-3, were anti-correlated (right half of Fig 2).

Gaussian feature centered at 1 MeV with a flux of 1.6×10^{-2} photons/cm^2-sec measured at $\sim 5\sigma$ significance. One model suggested[32] that the γ-ray feature was produced in a 4×10^9 K pair-dominated, optically thick cloud near the horizon, while hard x-rays ($E < 0.4$ MeV) were produced in a cooler, optically thinner, and ion-dominated plasma in the outer disk. Pairs may escape such a system and produced a narrow annihilation feature in the cold surrounding regions[33]. Such a feature was also seen by HEAO-3[34] at the predicted level of 4.4×10^{-4} photons/cm^2-sec, at $\sim 2\sigma$ significance.

5. SUMMARY

Cygnus X-1 has displayed two types of transitions over the last 30 years: (1) standard state to high x-ray state transition, and (2) standard state to superlow x-ray/ high γ-ray state transition. The former has been seen five times, but the latter was seen only once. The spectra for the three states are distinctly different. It is important to note that the shape of the standard state spectrum is harder in regions $E < 200$ keV and softer in $E > 200$ keV, compared to that of the high x-ray state spectrum. The terms "low/hard" and "high/soft" are therefore not accurate characterizations of the standard and high x-ray state spectra, respectively, when soft γ-ray component of the spectrum is taken into consideration. One of the outstanding unresolved questions for the past two decades is the absence of a second transition to the superlow x-ray/high γ-ray state, and thus the confirmation of the spectral features shown in its spectrum. If such a transition could be captured by INTEGRAL during its mission, the suite of INTEGRAL instruments are ideal to make sensitive measurements of these features, and to effectively address its triggering mechanism.

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