Gamma-Ray Spectral Variability of Cyg X-1

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Spectral States of Galactic Black Holes

The behavior of Cygnus X-1 is much like that seen in other galactic black hole sources.

HIGH STATE
“power-law γ-ray state”
high soft X-ray flux
low hard X-ray flux
“soft” X-ray spectrum

LOW STATE
“breaking γ-ray state”
low soft X-ray flux
high hard X-ray flux
“hard” X-ray spectrum

The nature of the variability at energies above 1 MeV has not been clearly established.

(from Grove et al. 1998)
Long-Term Variability of Cyg X-1

These data cover nearly the entire CGRO mission.
COMPTEL Observations

» COMPTEL provides the best data at energies above 1 MeV.

» Most COMPTEL data collected during the low X-ray state.

» COMPTEL also collected data during two high state periods:

  • **CGRO Viewing Period 318.1**

  • **CGRO Viewing Period 522.5**
    (Level of hard X-ray flux higher than that during VP 318.1.)

*Here we report on the results from an analysis of high state data collected during VP 522.5 and its comparison with a low state spectrum compiled from several weeks of CGRO data.*
Low State Spectrum  

» Contemporaneous broad-band spectrum using data from BATSE, OSSE and COMPTEL.

» Data selected for those periods with consistent hard X-ray flux.

» Photon spectrum shows evidence for emission out to ~ 5 MeV.

» Model fits originally performed in photon space. Recent analysis now incorporates full response information for both BATSE and OSSE.

» Standard Comptonization models are inadequate above ~1 MeV.

» A hybrid thermal / non-thermal model can provide an acceptable fit.

The spectrum requires a non-thermal component at high energies.
Hybrid Thermal / Non-Thermal Model

The XSPEC model COMPPS has been used to fit the data.

Models the data using an electron spectrum that consists of a thermal (Maxwellian) component plus a non-thermal (power-law) component.

The important parameters of the model include:

- the electron temperature \((kT_e)\)
- power-law index \((p_e)\) of the non-thermal component
- range \((\gamma_{\text{min}} \text{ and } \gamma_{\text{max}})\) of the non-thermal component
- optical depth of the corona \((\tau)\)
CGRO Viewing Period 522.5
(Target-of-Opportunity – high X-ray state)

» Soft X-ray increase began on 10 May 1996 (RXTE, 2-12 keV).
» Soft X-ray peak flux at 2 Crab on 19 May 1996 (pre-flare ~ 0.5 Crab)
» Correlated decrease in hard X-rays (BATSE, 20-200 keV).
» CGRO declared a target-of-opportunity (ToO) on June 13.
» CGRO pointing (OSSE, COMPTEL, EGRET) began on June 14.
» CGRO Z-axis pointed 5° from Cygnus X-1.
» ToO observation (CGRO viewing period 522.5) lasted 11 days.

This high state period is clearly seen in the X-ray time history (panel 3) between TJD 10200 and TJD 10350.
The 1-3 MeV COMPTEL image exhibited an unusually strong signal. No signal was visible at lower energies (0.75-1 MeV). This alone suggested that something unusual was taking place.
Flux Spectra

A comparison of low- and high-state spectra.

$E^2 \times \text{Flux Spectra}$

A comparison of low- and high-state spectra.

High State Spectrum

- A power-law with index of -2.6 provides a good fit to the data, with the power-law extending to at least 10 MeV.

- The data is also well fit with a hybrid thermal / non-thermal model.

- Good fits were obtained with three free parameters ($kT_e$, $p_e$, $\tau$).

- Two cases:
  1. Electron power law extending from $\gamma_{\text{min}} = 2$ to $\gamma_{\text{max}} = 1000$
  2. Electron power law extending from $\gamma_{\text{min}} = 2$ to $\gamma_{\text{max}} = 50$

The high energy power-law is inconsistent with emission from bulk motion Comptonization, which predicts a cutoff near 500 keV.
**Low State vs. High State**

*Electron power-law range* $\gamma_{\text{min}} = 2$ to $\gamma_{\text{max}} = 1000$

*hybrid model fits to data* $> 100$ keV

*Errors represent estimated 90% confidence levels*

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Low State</th>
<th>High State</th>
</tr>
</thead>
<tbody>
<tr>
<td>$kT_e$</td>
<td>$93 \ (+29,-12)$ keV</td>
<td>$55 \pm 8$ keV</td>
</tr>
<tr>
<td>$p_e$</td>
<td>$5.0 \ (+0.6,-0.4)$</td>
<td>$3.1 \pm 0.4$</td>
</tr>
<tr>
<td>$\tau$</td>
<td>$1.1 \pm 0.4$</td>
<td>$1.0 \ (+0.7,-0.5)$</td>
</tr>
<tr>
<td>$\chi^2$</td>
<td>$0.933$</td>
<td>$0.877$</td>
</tr>
<tr>
<td>$\nu$</td>
<td>$414$</td>
<td>$69$</td>
</tr>
</tbody>
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In the context of the hybrid model, the high state spectrum shows:

1) lower electron temperature
2) harder non-thermal electron component
3) no change in optical depth
**Low State vs. High State**

*Electron power-law range* $\gamma_{\text{min}} = 2$ to $\gamma_{\text{max}} = 50$

*hybrid model fits to data > 100 keV*

*Errors represent estimated 90% confidence levels*

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<tr>
<td>$kT_e$</td>
<td>$87 (+21,-10)$ keV</td>
<td>$46 (+6,-4)$ keV</td>
</tr>
<tr>
<td>$p_e$</td>
<td>$5.1 (+0.7,-0.5)$</td>
<td>$2.0 \pm 0.5$</td>
</tr>
<tr>
<td>$\tau$</td>
<td>$1.2 \pm 0.5$</td>
<td>$2.1 \pm 0.7$</td>
</tr>
<tr>
<td>$\chi$</td>
<td>$0.994$</td>
<td>$0.877$</td>
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1) lower electron temperature
2) harder non-thermal electron component
3) no change in optical depth
Physical Interpretation

The results are generally consistent with models that suggest a change in the inner disk radius (e.g., Poutanen & Coppi, 1998; Gierlinski et al. 1999)

LOW STATE

R$_{in}$ of thermal disk is large
more energy in corona
larger kT$_e$, larger p$_e$

*thermal component dominates*

HIGH STATE

R$_{in}$ of thermal disk is small
more energy in disk
lower kT$_e$, smaller p$_e$

*non-thermal component dominates*
Summary

» Composite CGRO spectra for both the low and high X-ray states.

» The spectra exhibit bimodal spectral behavior, as seen in other galactic black hole candidates, with pivot point near 1 MeV.

» Power-law spectrum of high state spectrum extends to at least 10 MeV, with no evidence for any cutoff.

» This is inconsistent with *bulk motion Comptonization* models that predict a cutoff near 500 keV.

» A hybrid thermal/non-thermal model can describe the data.

» The results are generally consistent with a smaller inner disk radius for the high state (smaller $kT_e$ during high state).

» There is also evidence for additional non-thermal acceleration during high state (smaller $p_e$ during high state).