Gamma-Ray Spectral Variability of Cyg X-1

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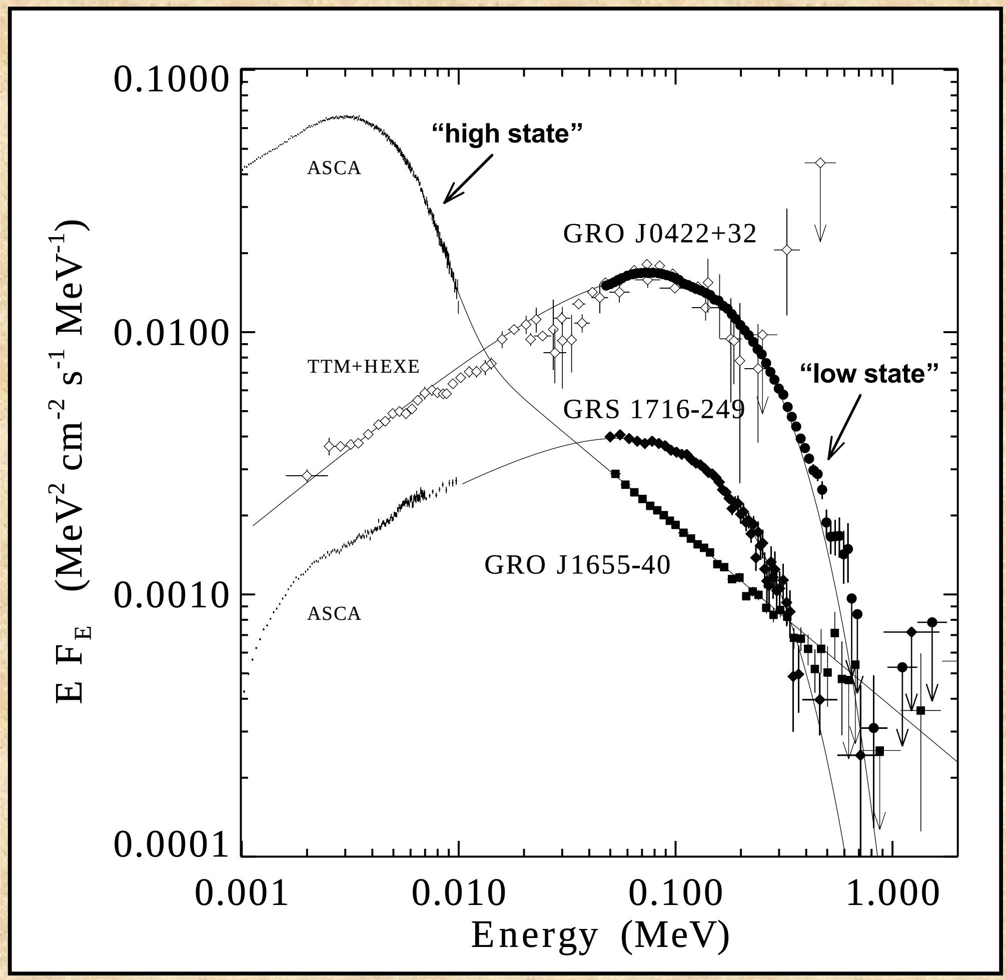
Spectral States of Galactic Black Holes

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



(from Grove et al. 1998)

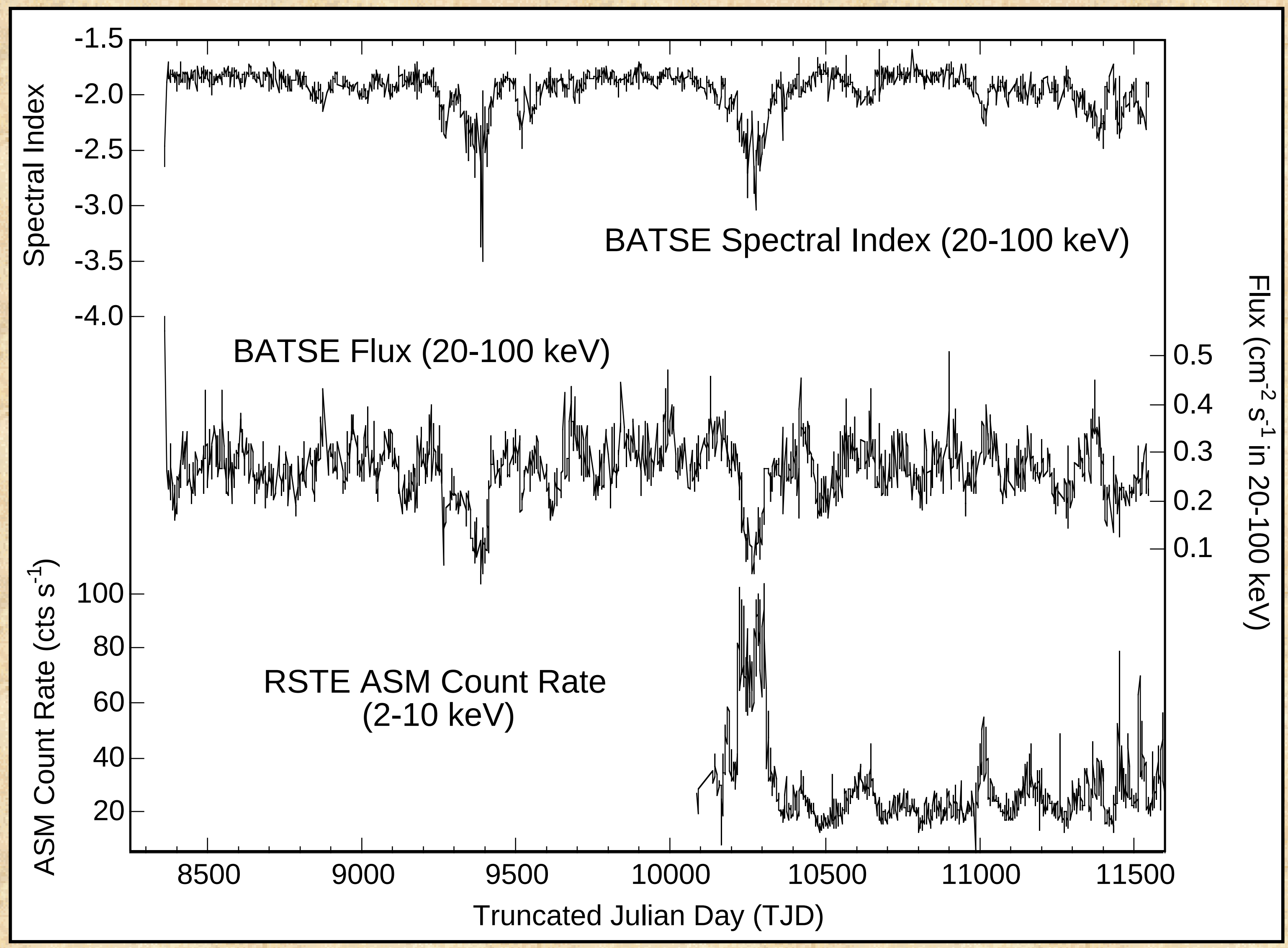
LOW STATE
"breaking γ-ray state"
low soft X-ray flux
high hard X-ray flux
"hard" X-ray spectrum

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

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

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:**

- ***<u>CGRO Viewing Period 318.1</u>***
  February 1-8, 1994. Not seen by COMPTEL.
  Consistent with extrapolation of hard X-ray spectrum.

- ***<u>CGRO Viewing Period 522.5</u>***
  June 14-25, 1996. Significant signal seen by COMPTEL.
  Consistent with extrapolation of hard X-ray spectrum.
  (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

McConnell et al., ApJ, 543, 928 (2000)

- **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.
Poutanen & Svensson – ApJ, 470, 249 (1996)

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 (γ_{min} and γ_{max}) of the non-thermal component**
- **optical depth of the corona (τ)**

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.**

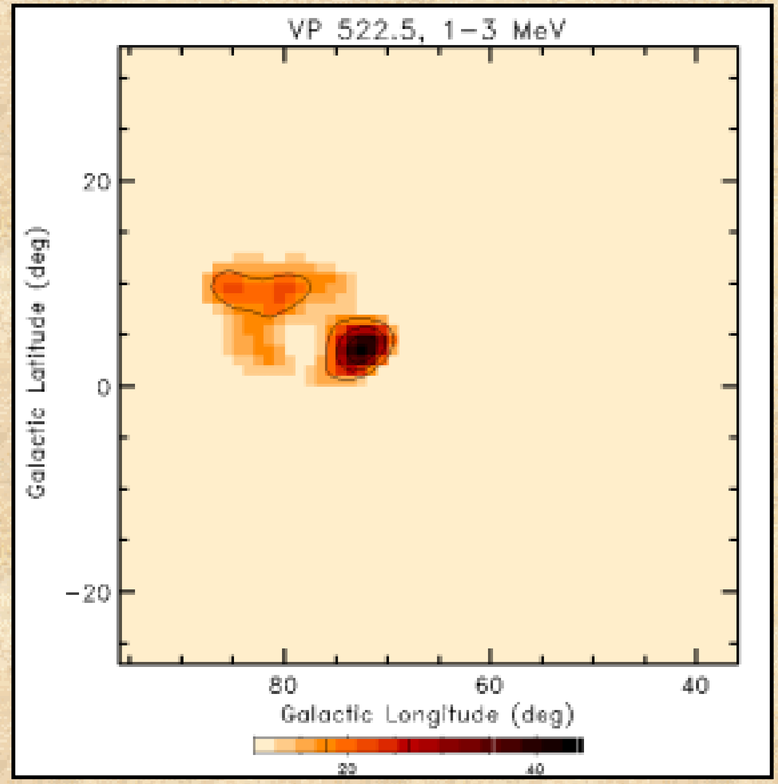
This high state period is clearly seen in the X-ray time history (panel 3) between TJD 10200 and TJD 10350.

COMPTEL Imaging - VP 522.5

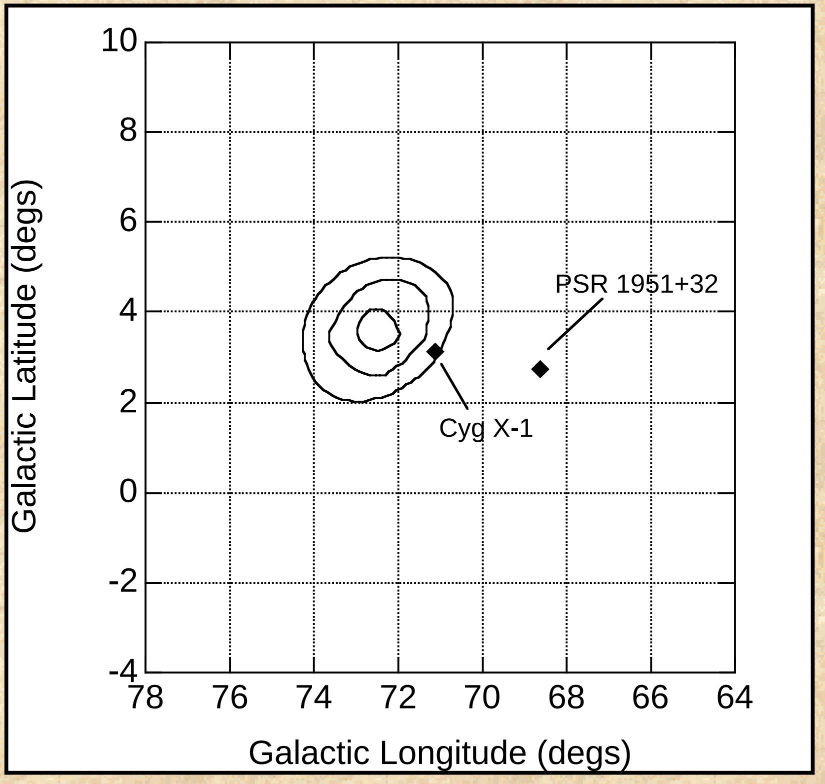
The 1-3 MeV COMPTEL image exhibited an unusually strong signal.

No signal was visible at lower energies (0.75-1 MeV).

This alone suggested that something unusual was taking place.



Likelihood Map

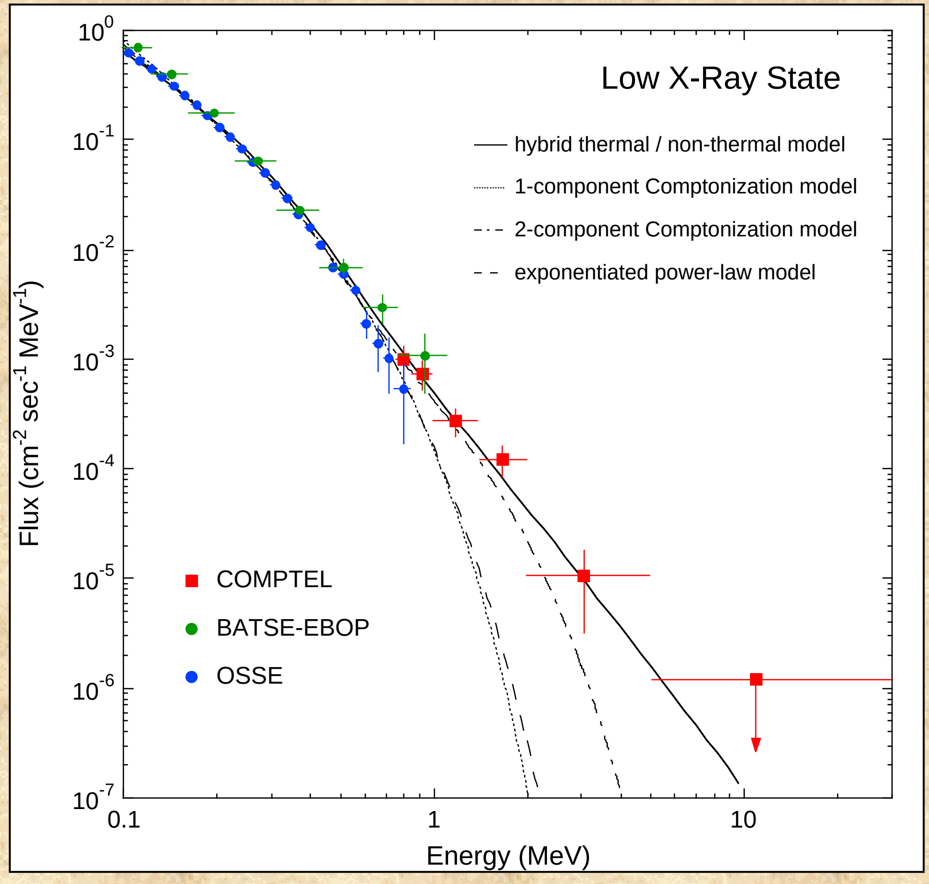


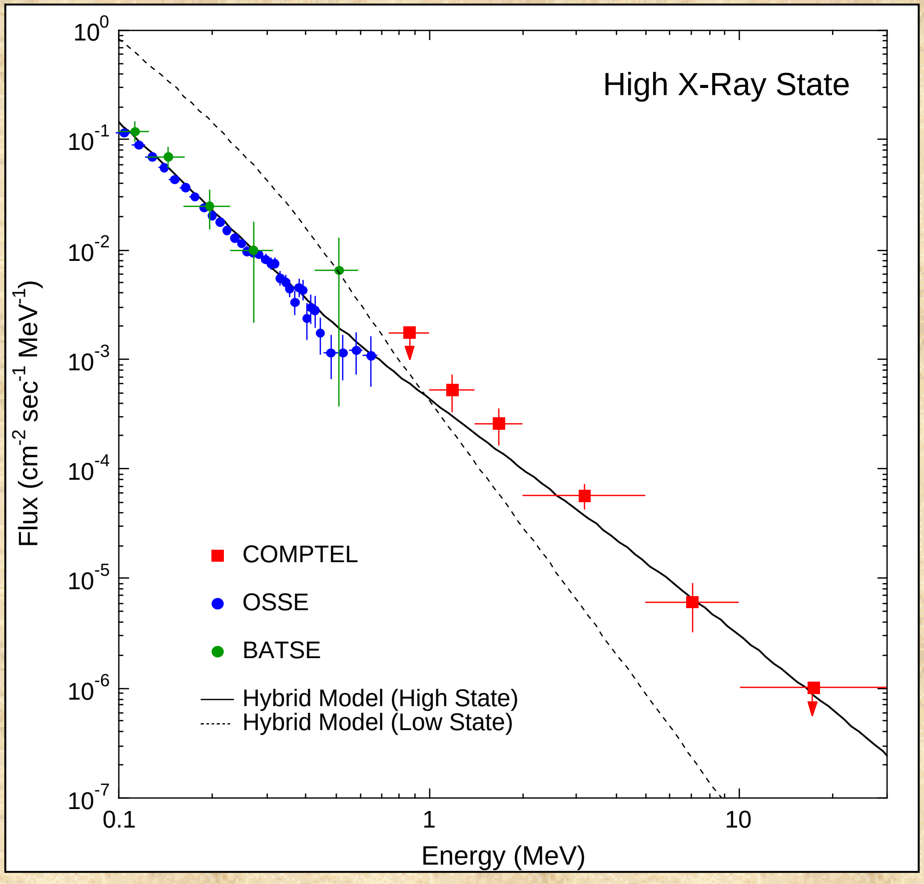
Location Contour Map

(note different scale)

Flux Spectra

A comparison of low- and high-state spectra.

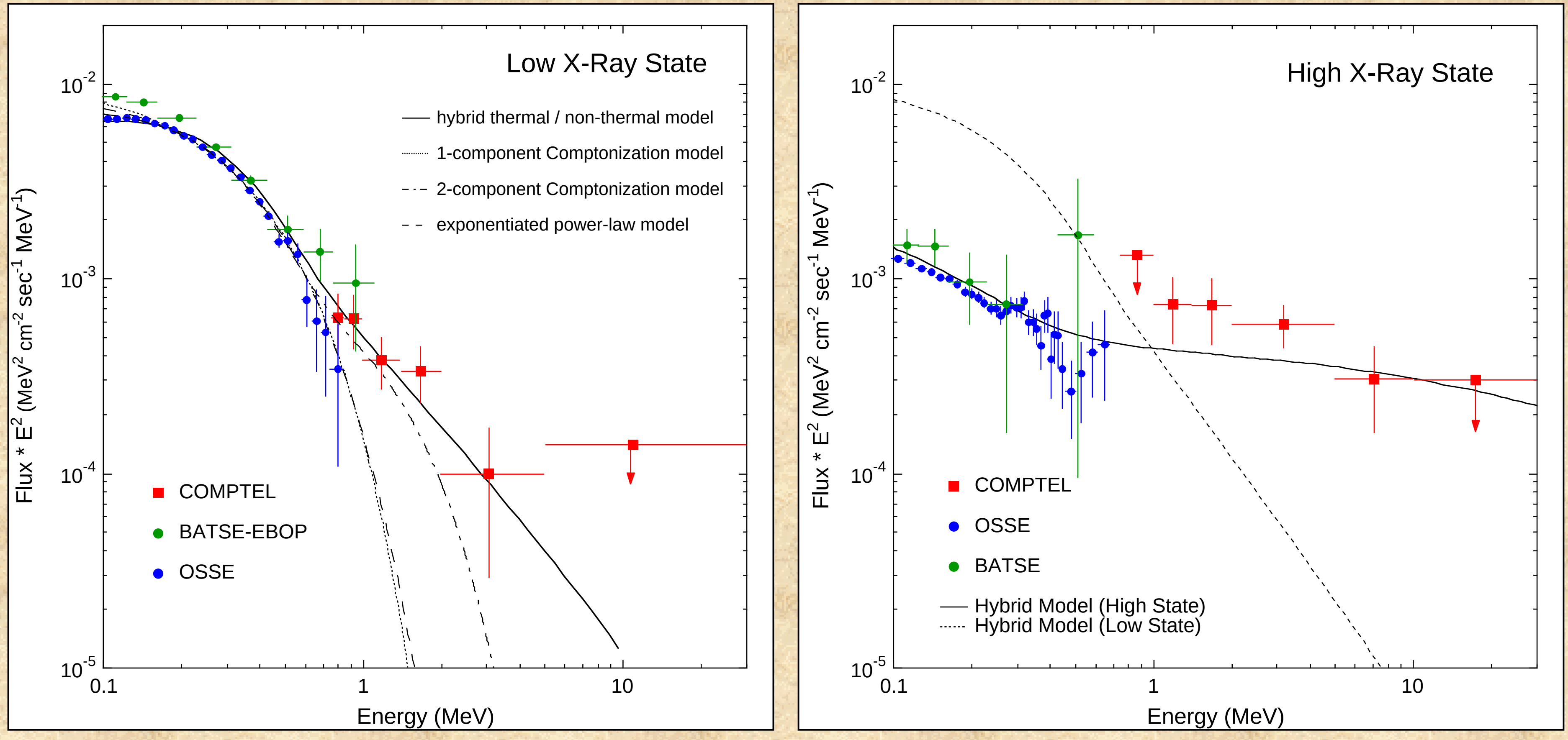




McConnell et al., ApJ, 543, 928 (2000)

E^2 x Flux Spectra

A comparison of low- and high-state spectra.



McConnell et al., ApJ, 543, 928 (2000)

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

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 γ_{min} = 2 to γ_{max} = 1000

hybrid model fits to data > 100 keV

Errors represent estimated 90% confidence levels

Parameter	*Low State*	*High State*
kT_e	93 (+29,-12) keV	55 ± 8 keV
p_e	5.0 (+0.6,-0.4)	3.1 ± 0.4
τ	1.1 ± 0.4	1.0 (+0.7,-0.5)
χ_ν	0.933	0.877
ν	414	69

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 γ_{min} = 2 to γ_{max} = 50

hybrid model fits to data > 100 keV

Errors represent estimated 90% confidence levels

Parameter	*Low State*	*High State*
kT_e	**87 (+21,-10) keV**	**46 (+6,-4) keV**
p_e	**5.1 (+0.7,-0.5)**	**2.0 ± 0.5**
τ	**1.2 ± 0.5**	**2.1 ± 0.7**
χ_ν	**0.994**	**0.877**
ν	**414**	**69**

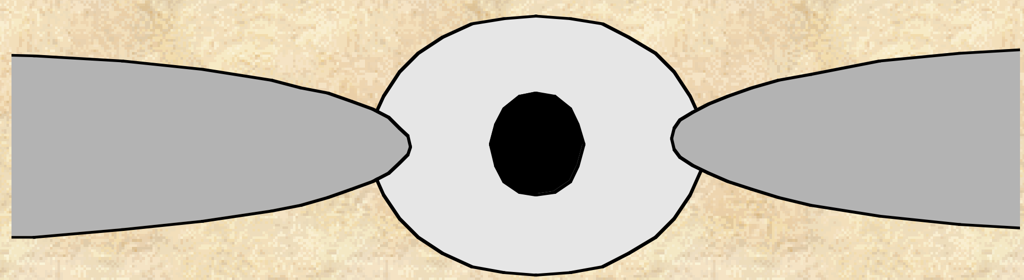
In the context of the hybrid model, the high state spectrum shows:

1) lower electron temperature
2) harder non-thermal electron component
3) no change in optical depth

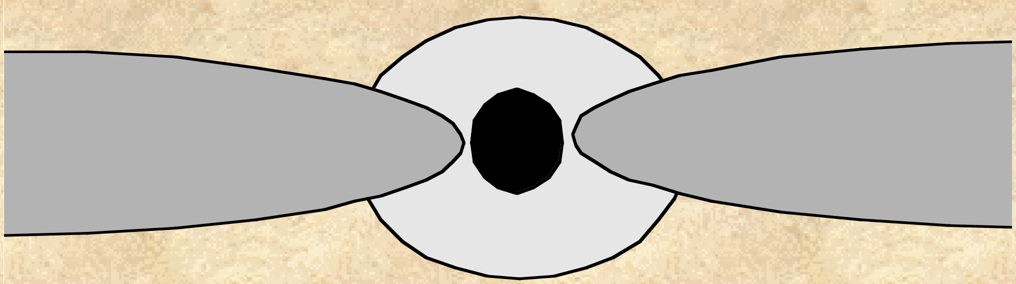
Physical Interpretation

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 X-RAY STATE



HIGH X-RAY STATE



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).**