Spectral Variability of Cyg X-1 at Energies Above 1 MeV

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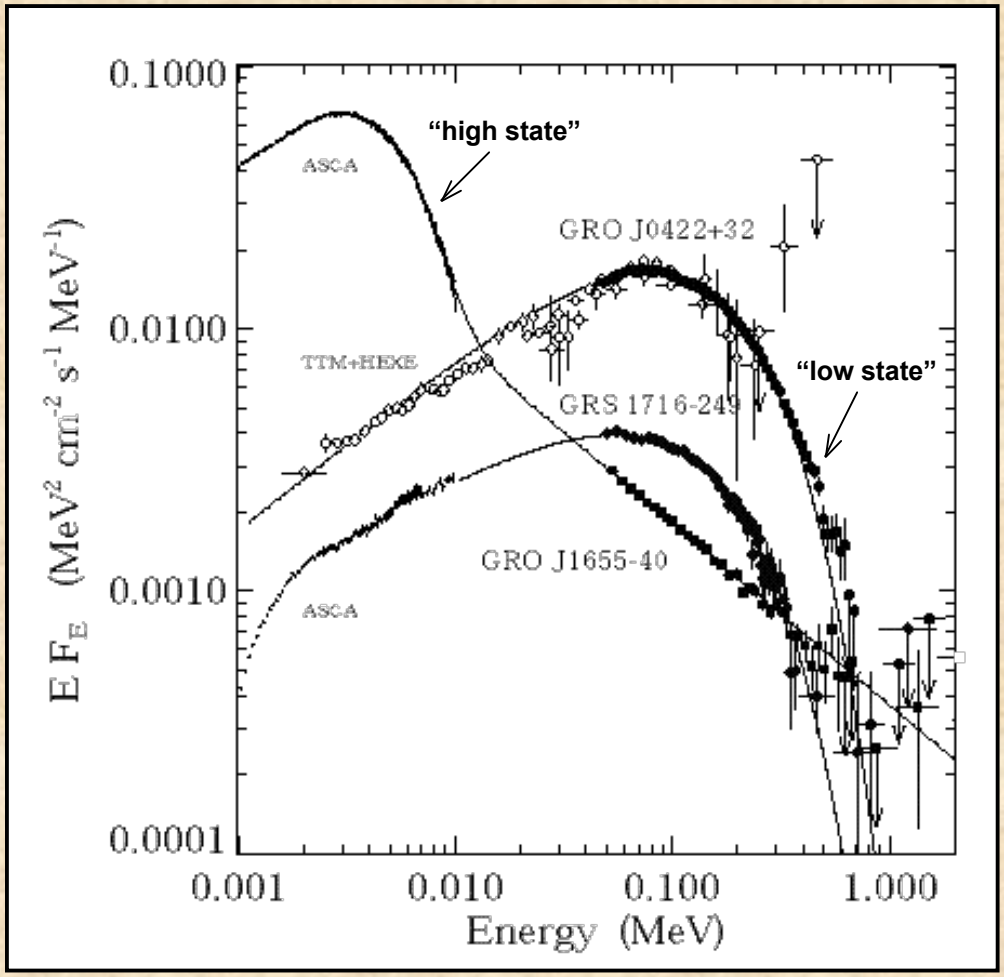
Spectral States of Galactic Black Holes

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



(from Grove et al. 1998)

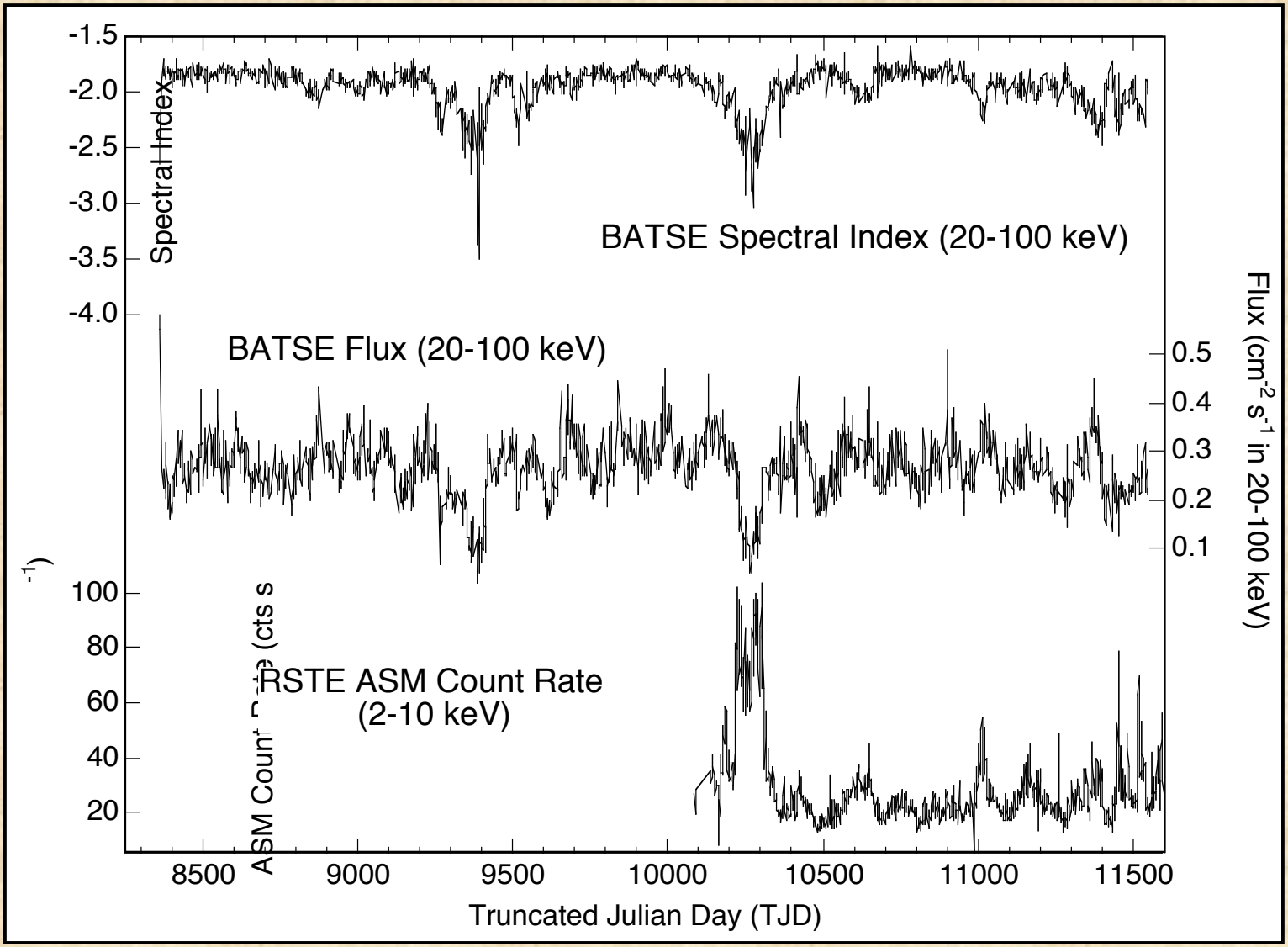
LOW STATE
"breaking -ray state"
low soft X-ray flux
high hard X-ray flux
"hard" X-ray spectrum

HIGH STATE
"power-law -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 X-Ray Flux

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***
  February 1-8, 1994. Not seen by COMPTEL.
  Consistent with extrapolation of hard X-ray spectrum.

- ***CGRO Viewing Period 522.5***
  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.)

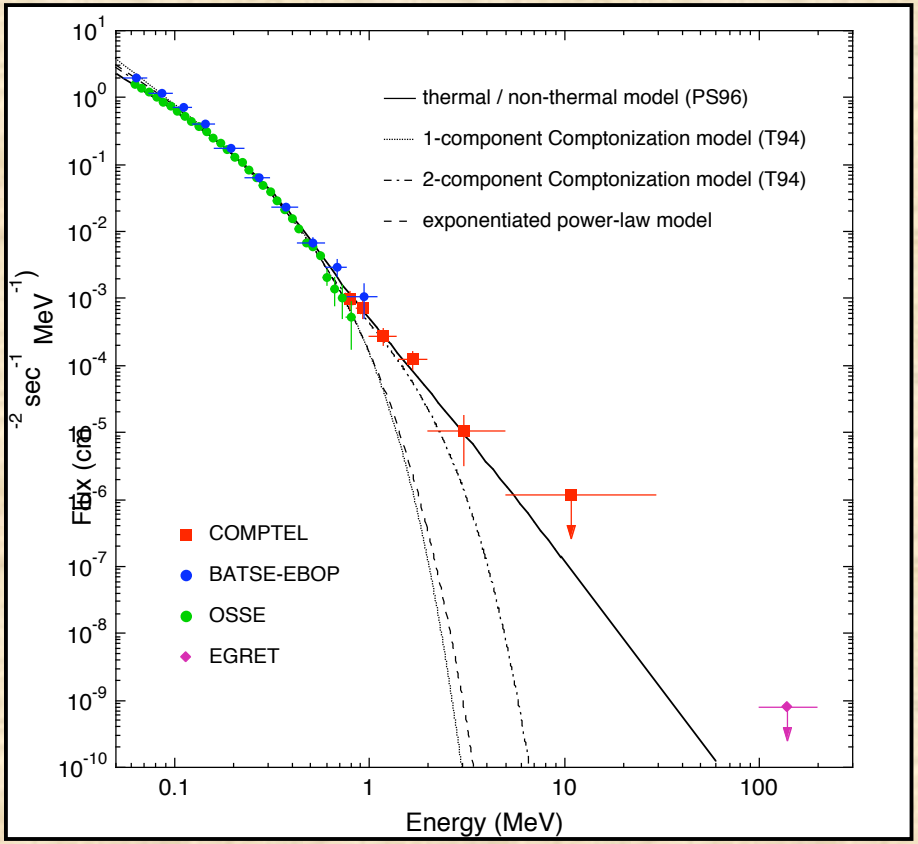
Here we report on the results from an analysis of high state data collected during VP 522.5 and its comparison with a low state spectrum compiled from several weeks of CGRO data.

Low State Spectrum

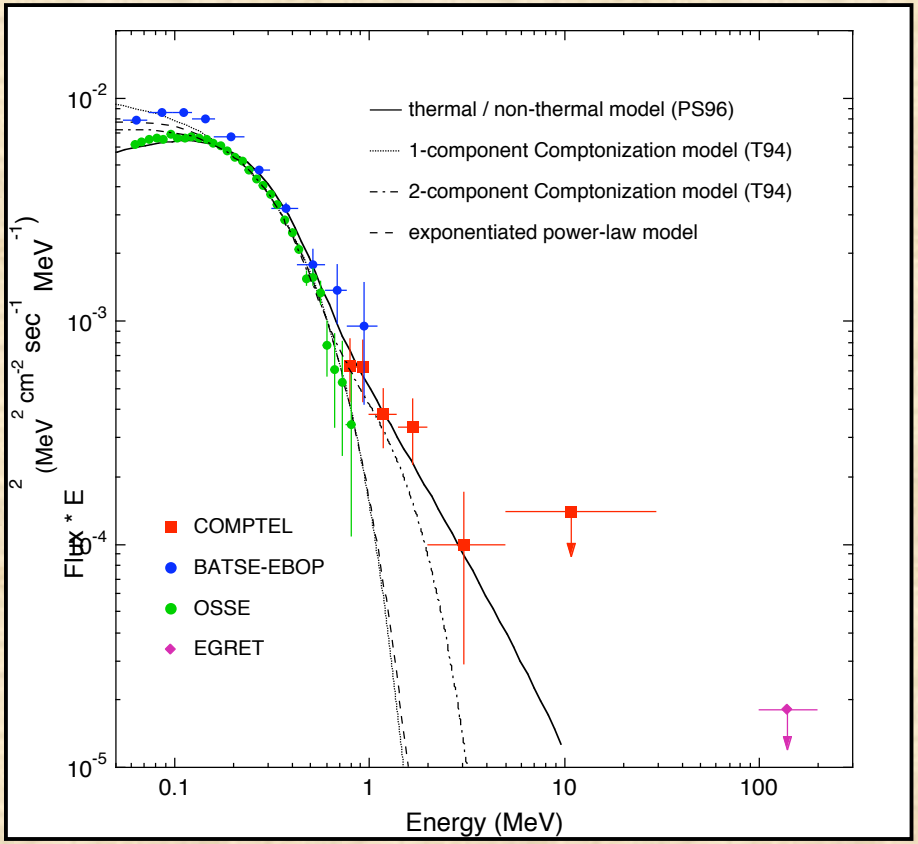
Contemporaneous CGRO Spectra

Compiled from data collected during first three years of CGRO mission

McConnell et al., in press, ApJ, v544 (20-Nov-2000)



Flux Spectrum



E^2 ▯ Flux Spectrum

Low State Spectrum

- Contemporaneous broad-band spectrum using data from BATSE, OSSE and COMPTEL (McConnell et al., 2000).
- 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 free parameters of the model include :

- **the electron temperature (kT_e)**
- **power-law index (p_e) of the non-thermal component**
- **low-energy cutoff (γ_{min}) of non-thermal component (γ_{max} = 10000)**
- **optical depth of the corona (τ)**
- **amplitude to fit BATSE spectrum (A_{BATSE})**
- **amplitude to fit OSSE spectrum (A_{OSSE})**
- **amplitude to fit COMPTEL spectrum ($A_{COMPTEL}$)**

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.

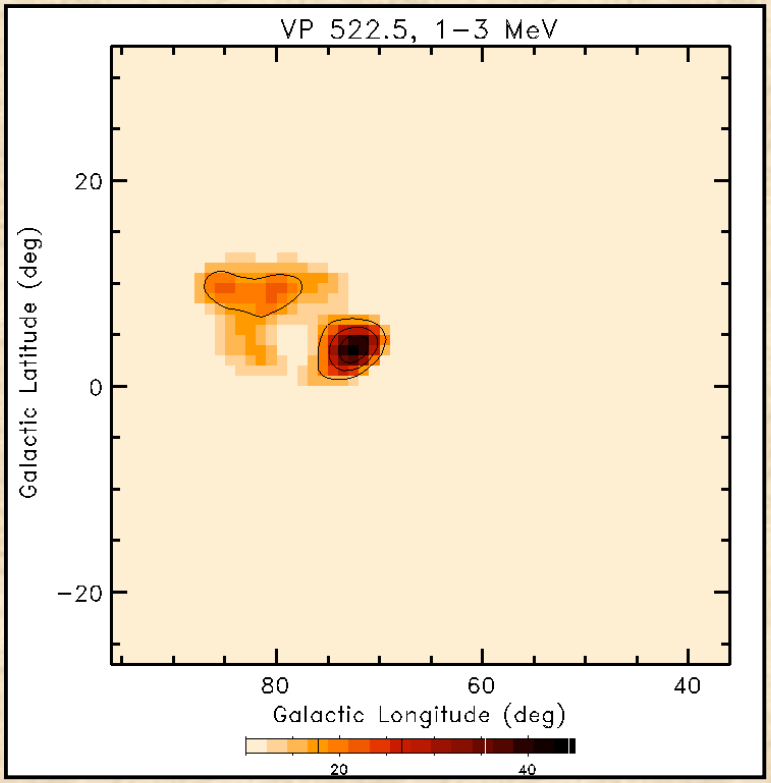
This high state period is clearly seen in the X-ray time history (panel 3) between TJD 10200 and TJD 10350.

COMPTEL Imaging - VP 522.5

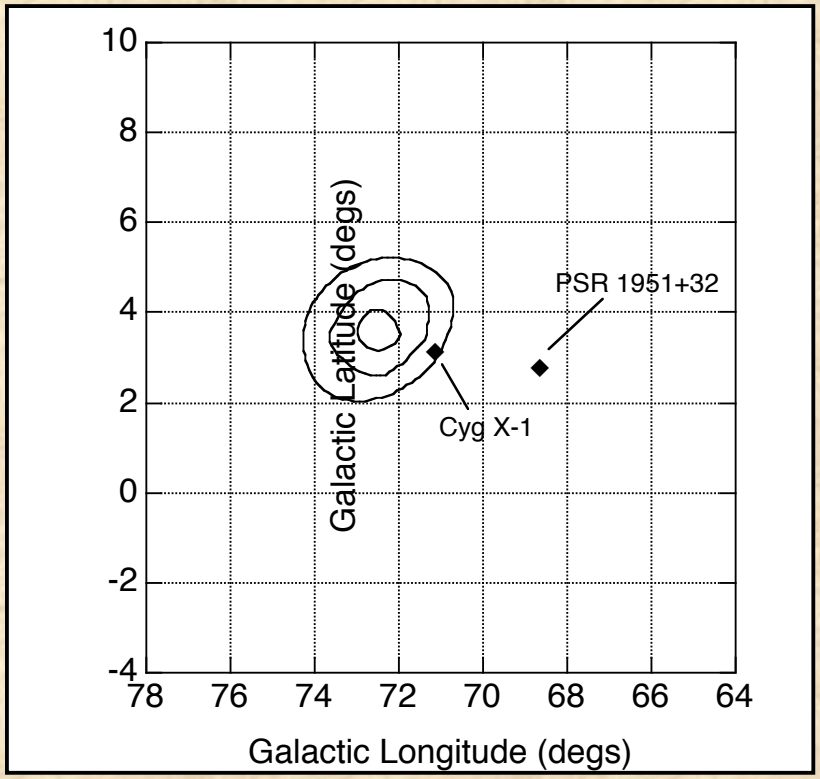
The 1-3 MeV COMPTEL image exhibited an unusually strong signal.

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

This fact alone suggested that something unusual was taking place.



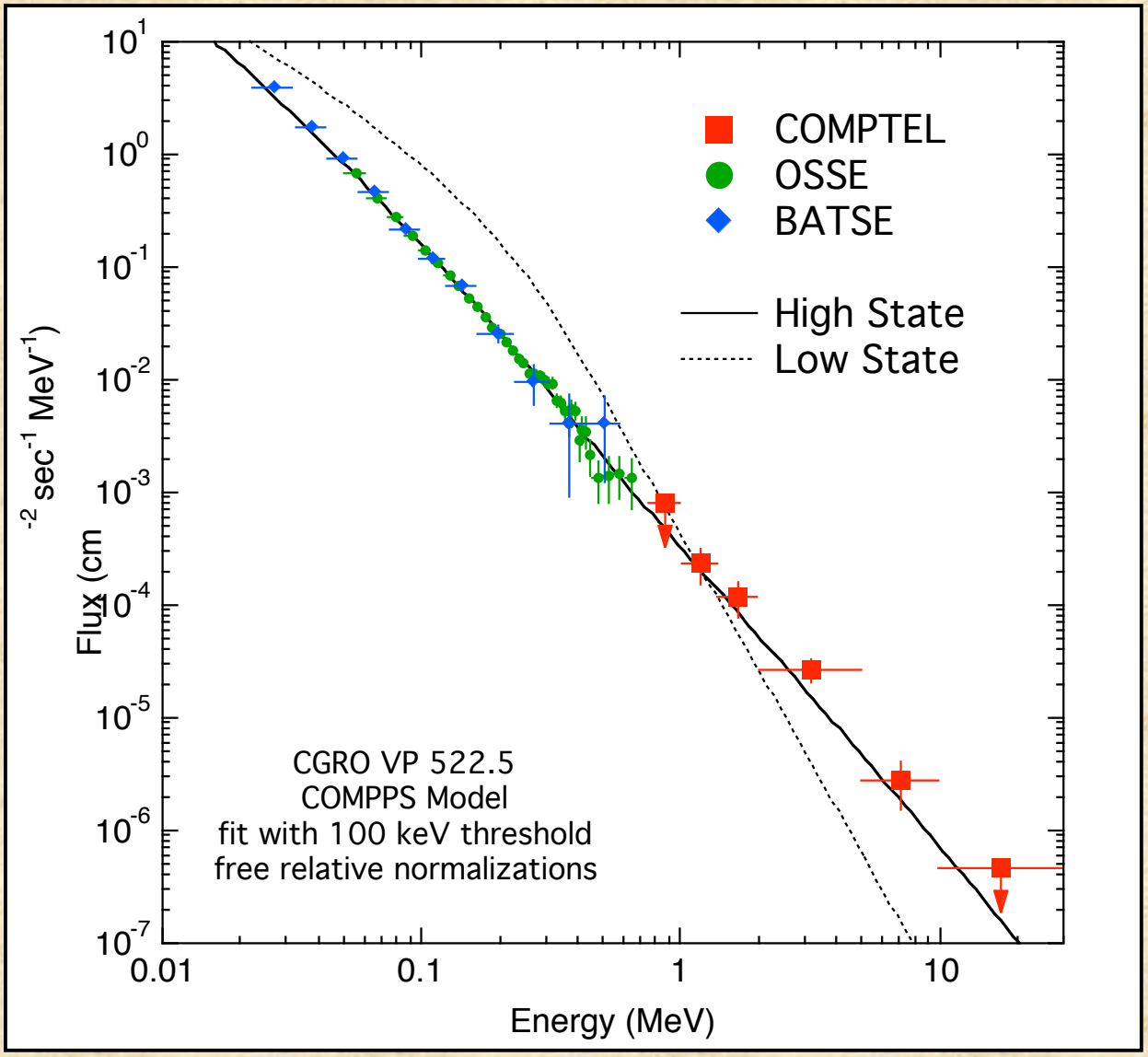
Likelihood Map



Location Contour Map
(note different scale)

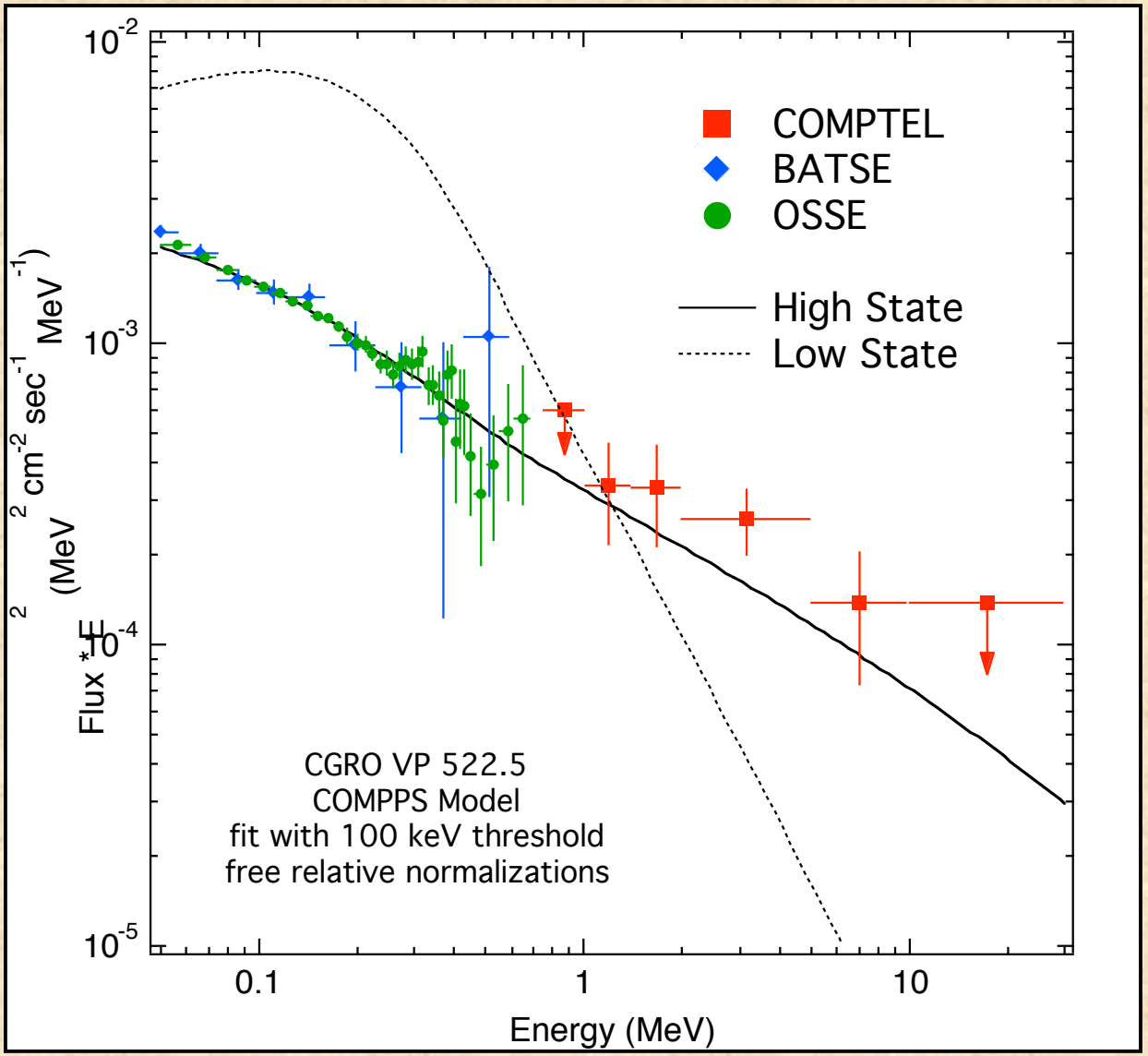
High State Spectrum - VP 522.5

Flux Spectrum



High State Spectrum - VP 522.5

E² ∫ Flux Spectrum



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.
- Both model fits, unlike that for the low state, require a large (factor of ~1/3) normalization of the COMPTEL data.
- The reason for this large normalization is not entirely understood. Here we assume this to represent a response normalization.

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

hybrid model fits to data > 100 keV

Parameter	*Low State*	*High State*
kT	64 ± 4 keV	66 ± 9 keV
p_e	5.0 ± 0.3	3.8 ± 0.3
τ_{min}	1.6	1.8
τ	2.6 ± 0.6	0.6 ± 0.4
A_{BATSE}	1.02	4.62
A_{OSSE}	0.87	3.79
$A_{COMPTEL}$	1.08	10.21

Errors represent estimated 90% confidence levels.

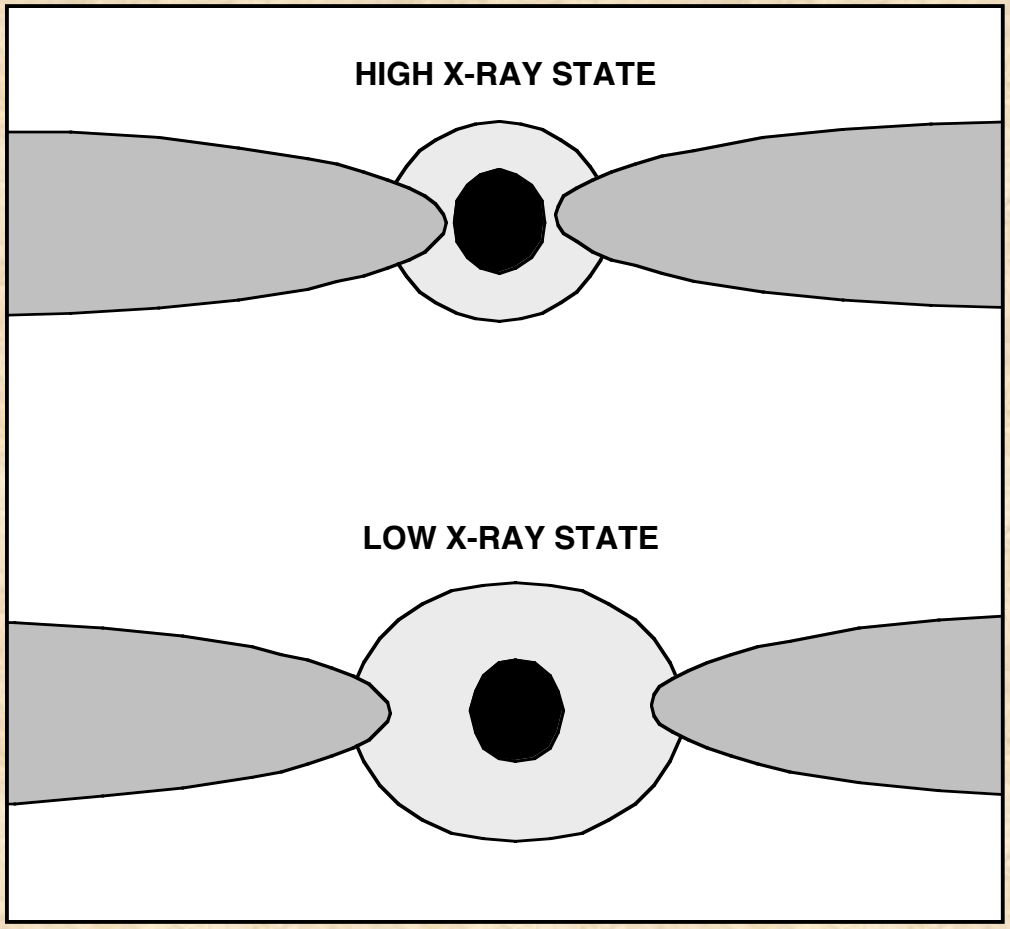
These data are preliminary.
A more complete analysis is in progress.

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

1) smaller optical depth
2) harder non-thermal electron component
3) same electron temperature

Physical Interpretation

Poutanen & Coppi (1998)



HIGH STATE

smaller optical depth

smaller thermal component

non-thermal component dominates

LOW STATE

larger optical depth

larger thermal component

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 models that describe the emission in terms of *bulk motion Comptonization*, which predict a cutoff near 500 keV.
- A hybrid thermal/non-thermal model can describe the data.
- The results are consistent with the model of Poutanen & Coppi (1998), although a predicted decrease in kT_e for the high state is not seen.