Spectral Evolution in Markarian 421

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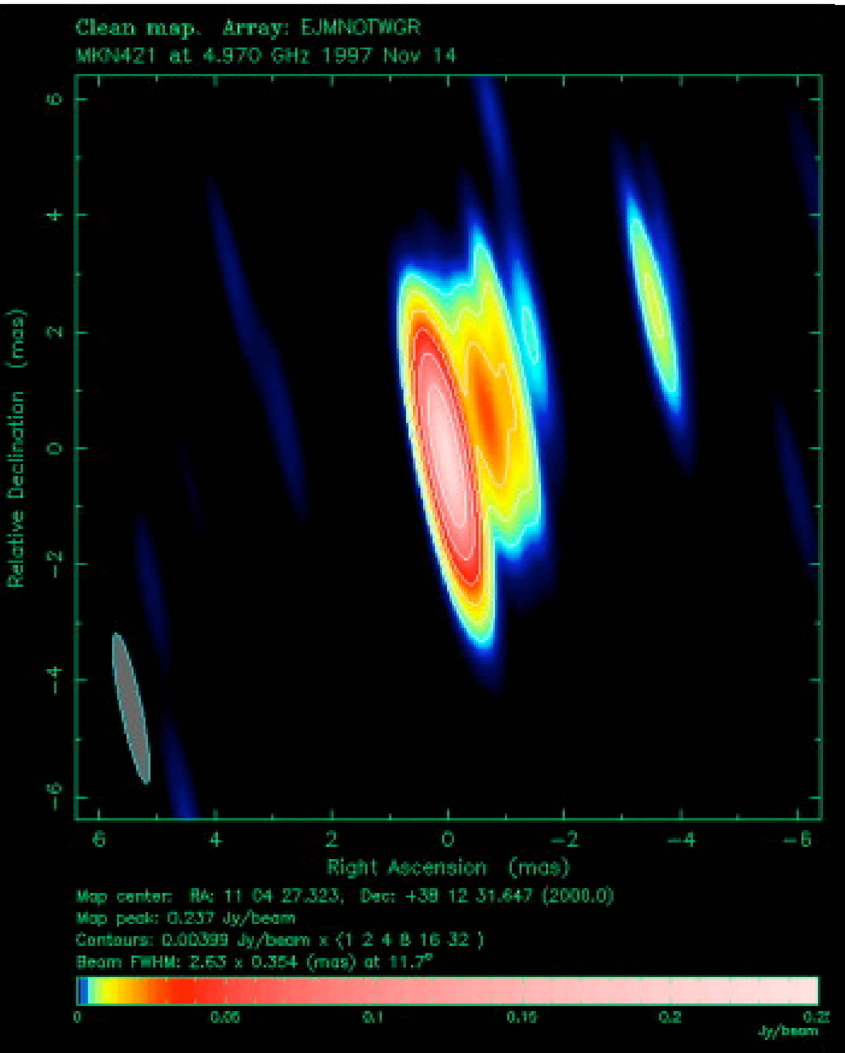
DPF Meeting Riverside, CA
30 Aug. 2004

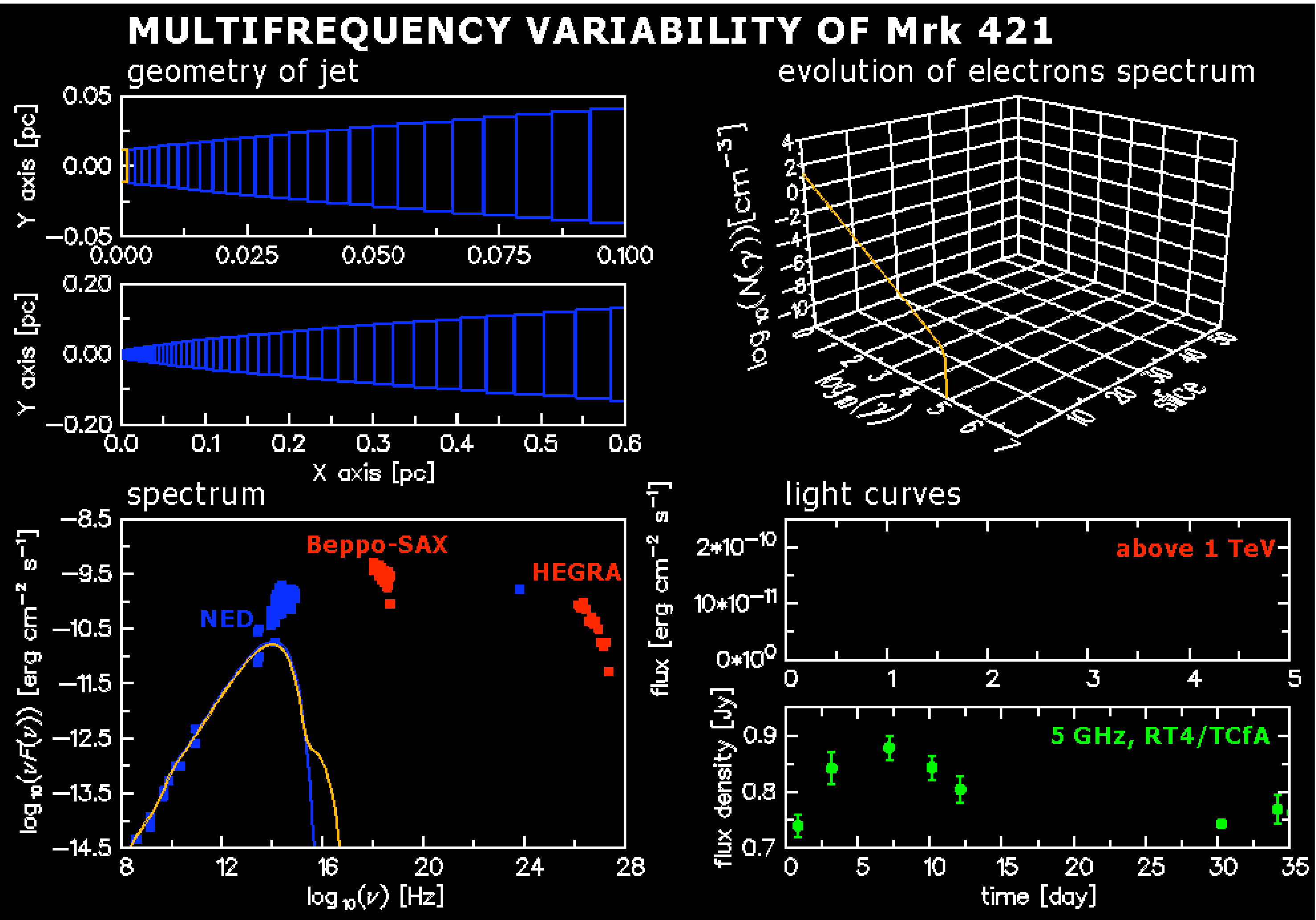
Mrk 421

Radio Emission - A large elliptical galaxy with a core-jet structure. VLBI images on parsec scales suggest a slow moving jet oriented within a few degrees to our line of sight (Piner & Edwards 2004).

High Energy Emission - Closest (z = 0.031) and most intensely studied TeV Blazar, first detected at TeV energies with the Whipple 10m telescope in 1992. Rapid, bright variability of the compact X-ray and TeV emitting regions (within 0.1 pc to the jet base) imply relativistic jet motion at this scale. Evidence of severe jet deceleration suggest less extreme values of physical parameters, including the jet Doppler factor, than derived by standard one-zone synchrotron self-Compton (SSC) emission models (Georganopoulos & Kazanas 2003; Ghisellini, Tavecchio & Chiaberge 2004).

(Katarzynski 2003)





Contribution to Blazar Studies

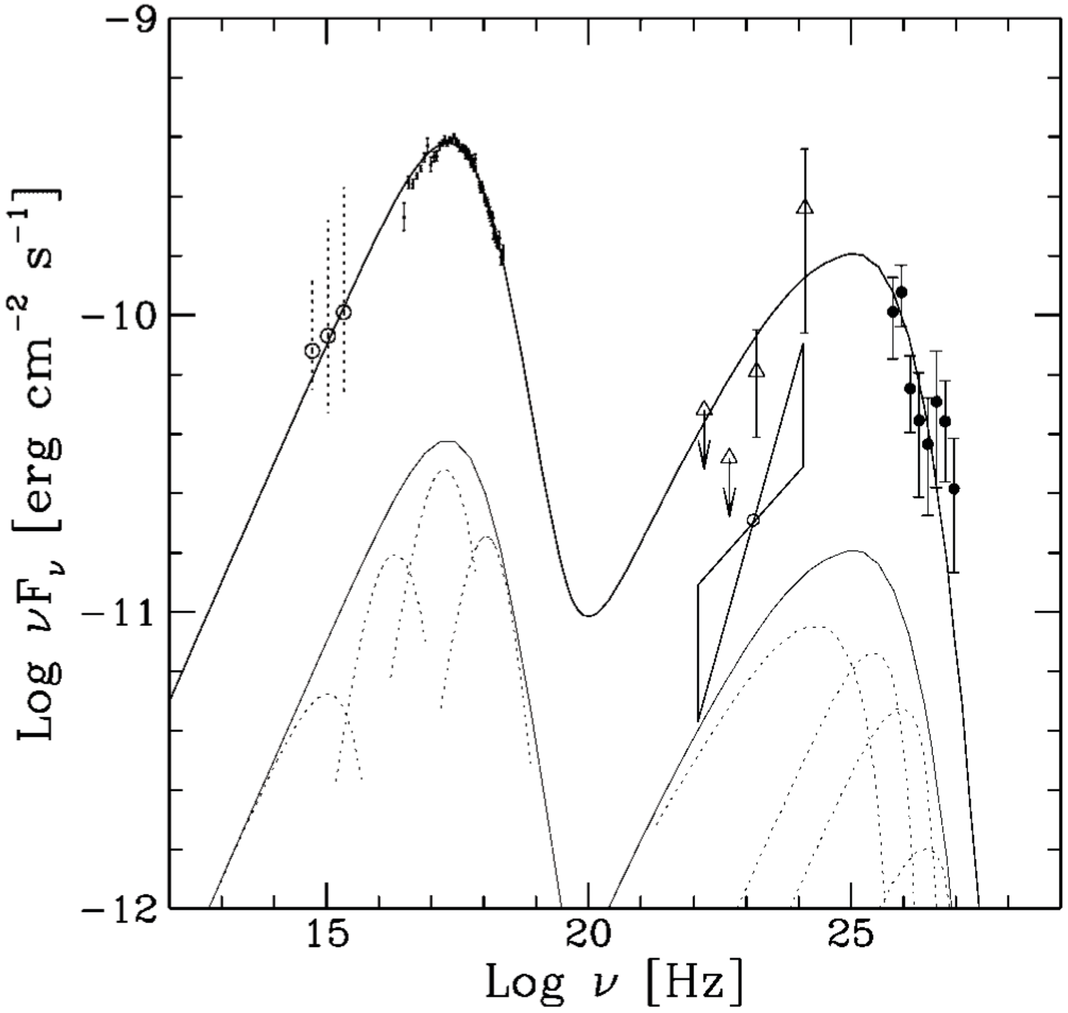
Advantages over powerful Blazars

- Inverse Compton component extends to TeV range (flaring spectra on hour timescales).

- Peak in synchrotron emission at X-ray energies, individual flares visible (UV is highly absorbed, and overwhelmed by external radiation).

Simultaneous Spectrum

Due to the rapid flaring observed at X-ray and TeV energies, degeneracies in source conditions and particle injection given by various model fits can be resolved (Krawczynski 2002).



Simultaneous Whipple 10m (TeV) and BeppoSAX (X-ray) observations from 1998, with archival optical, UV, and GeV data shown. The solid curve is a fit to the homogeneous SSC model. The BeppoSAX data was fit with a continuous broken powerlaw, while the Whipple data is given as a simple powerlaw (Maraschi et al. 1999).

X-ray Spectral Curvature

Evolution of the peak synchrotron energy Ep and a simple model of particle acceleration is found through a log-parabolic fit:

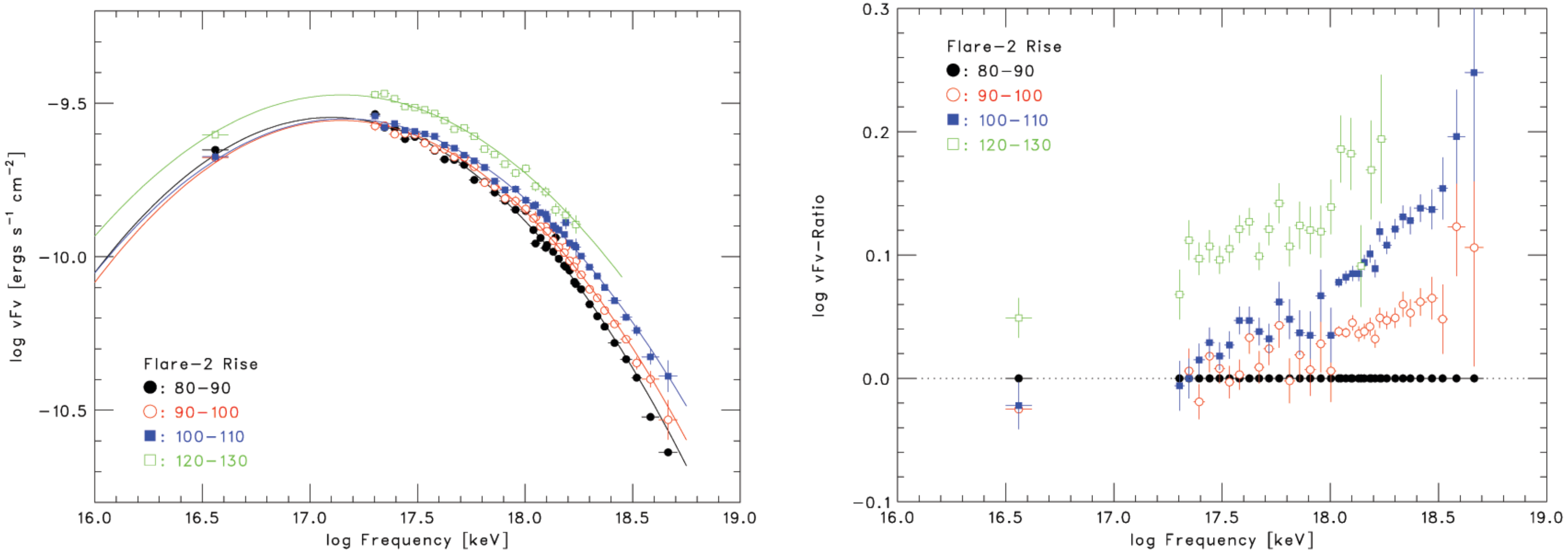
$$F(E) = K*(E/E_1)^{-(a+b*Log(E/E_1))}$$

Shifts in Ep from 0.5 - 2 keV are well correlated with the peak flux.

Possible injection of higher energy components causing the synchrotron flaring has prompted fits with a steady quiescent curve and a variable curve in the hard X-ray range.

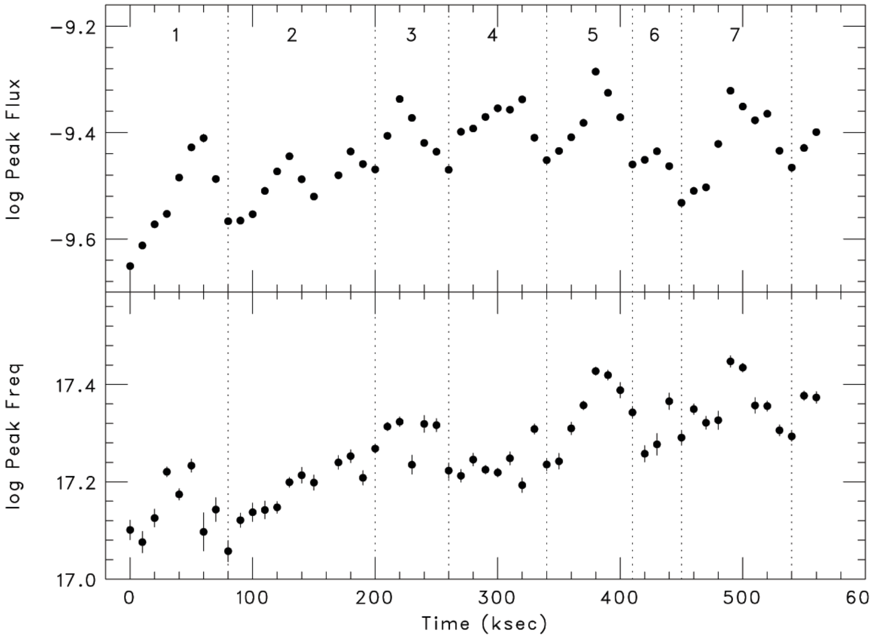
A detailed investigation of the 2003 observations shown later is underway.

(a) (b)



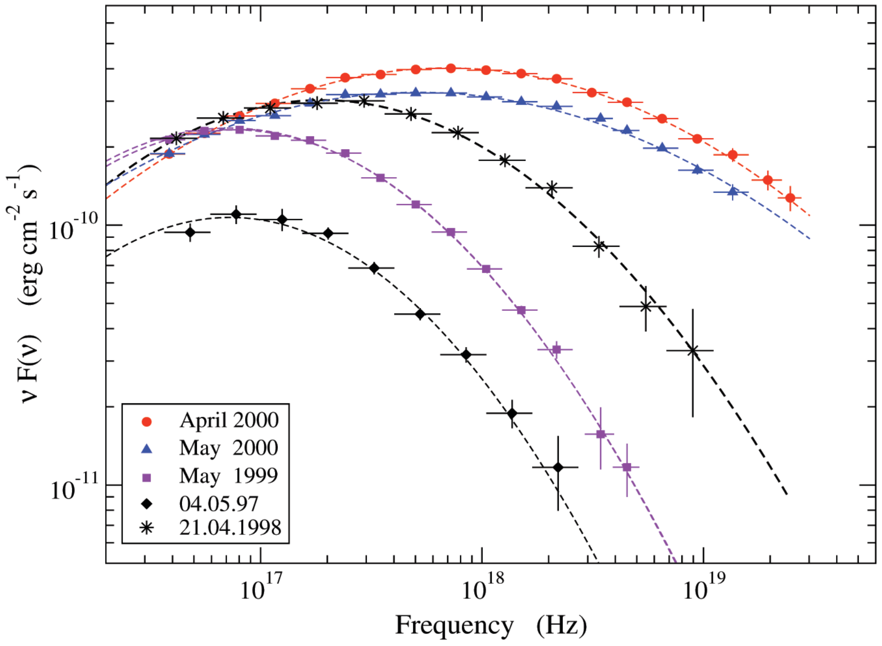
(a), (b) Spectrum from ASCA and RXTE observations (covering 0.8 - 18 keV) in 1998. The high energy end rises first, and then the entire spectrum levels off, suggesting a high energy component initiated the flare (Tanihata 2001).

(c)



(c) Evolution of the peak synchrotron energy and flux states, derived by log-parabolic fits of ASCA observations in 1998 (Tanihata 2001).

(d)

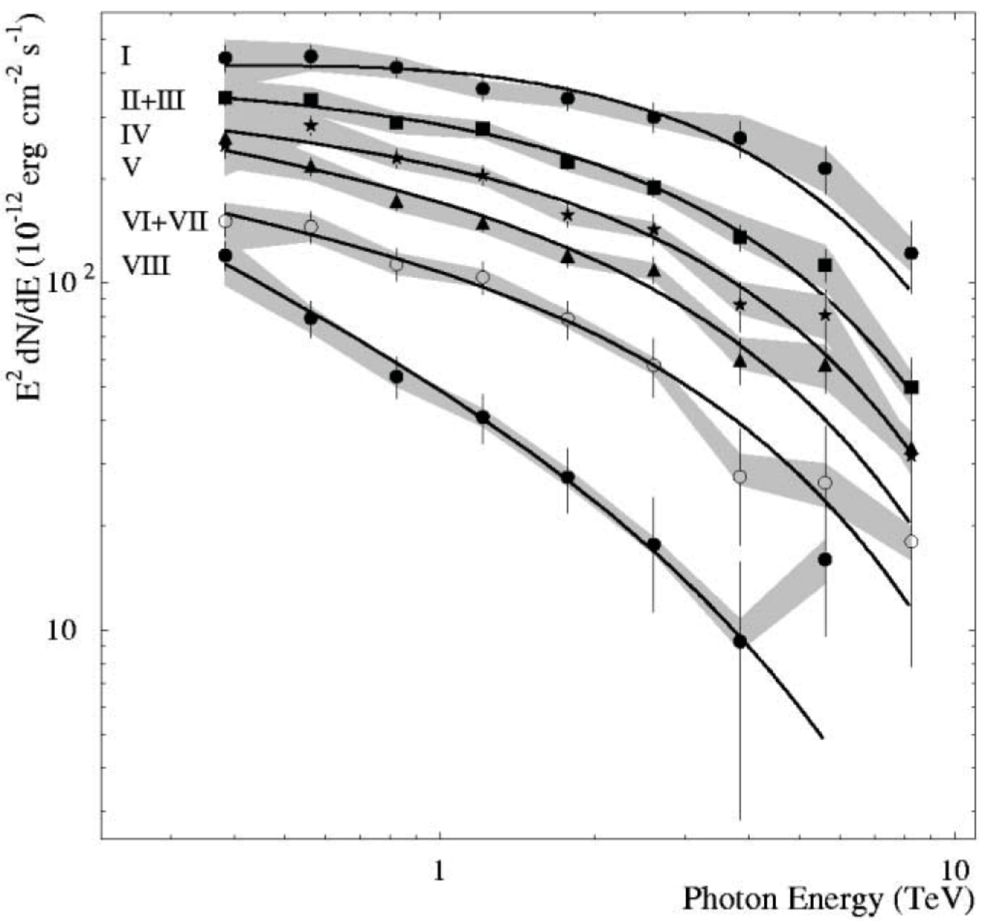


(d) BeppoSAX spectrum from observations over 1997 to 2000 (Massaro et al. 2004).

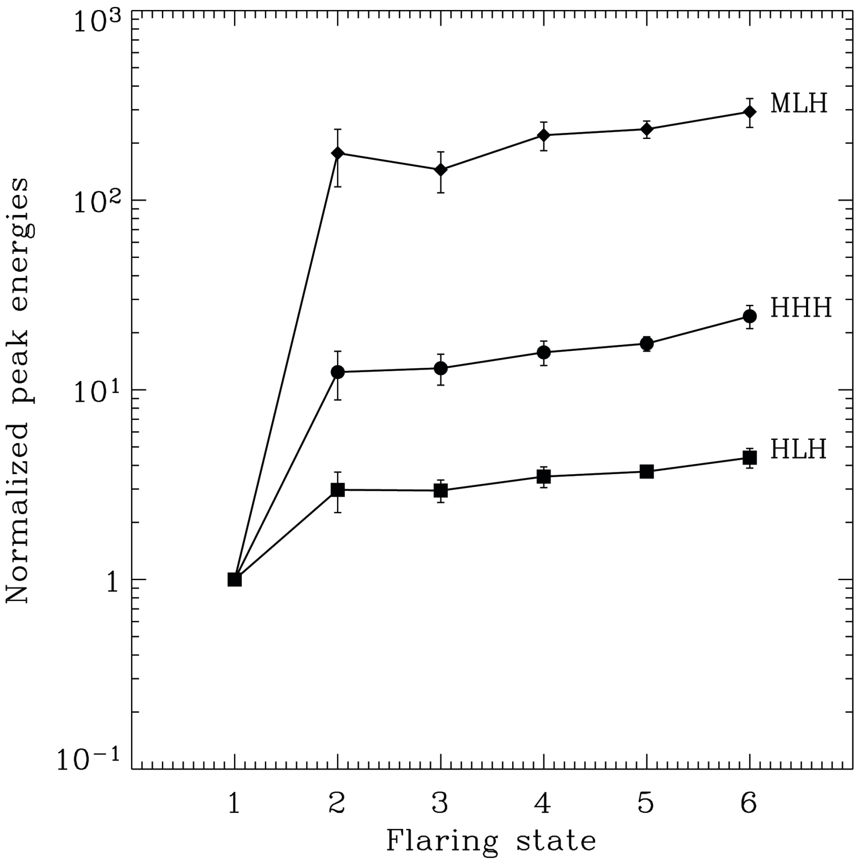
TeV Spectral Curvature

Significant absorption by the IR extragalactic background light (EBL) flattens the spectrum from ~1 - 10 TeV. Corrected spectra are well described by a log-parabolic fit with peak inverse-Compton values from 0.5 - 1.2 TeV (Dwek & Krennrich 2004).

To achieve adequate statistics, detailed spectral evolution studies require strong flaring states observations. A short-term variability study is underway by Krennrich et al. for the 2001 flare.



Whipple 10m observations of Mrk 421 in 2001 fit with an exponential cutoff (Krennrich et al. 2002).



Same Whipple 10m data as (left) absoption corrected for three different EBL realizations. A correlation of peak energy and flux state is shown (Dwek & Krennrich 2004).

Observations: Lightcurves

The Whipple 10m imaging atmospheric Cherenkov telescope (IACT) atop Mt. Hopkins, Arizona utilizes a 331 PMT 3-fold triggering camera at the focal point of the 10 meter diameter reflector, and is sensitive above 390 GeV.

Gamma-ray images are selected from the 99 % cosmic ray background through cuts (SuperCuts2000) on the Hillas image shape parameters. All data was taken in *Tracking* mode (28 min. staring observation) above 30 degrees zenith angle, and are normalized to the observed Crab flux from each season.

The RXTE satellite misson launched in Dec. 1995 was designed and built by the GSFC for NASA. On board are two pointed instruments, the PCA (2 - 25 keV), and the HEXTE (20 - 100 keV). In addition, the All-Sky Monitor (ASM) built by MIT scans about 80 % of the sky on every orbit.

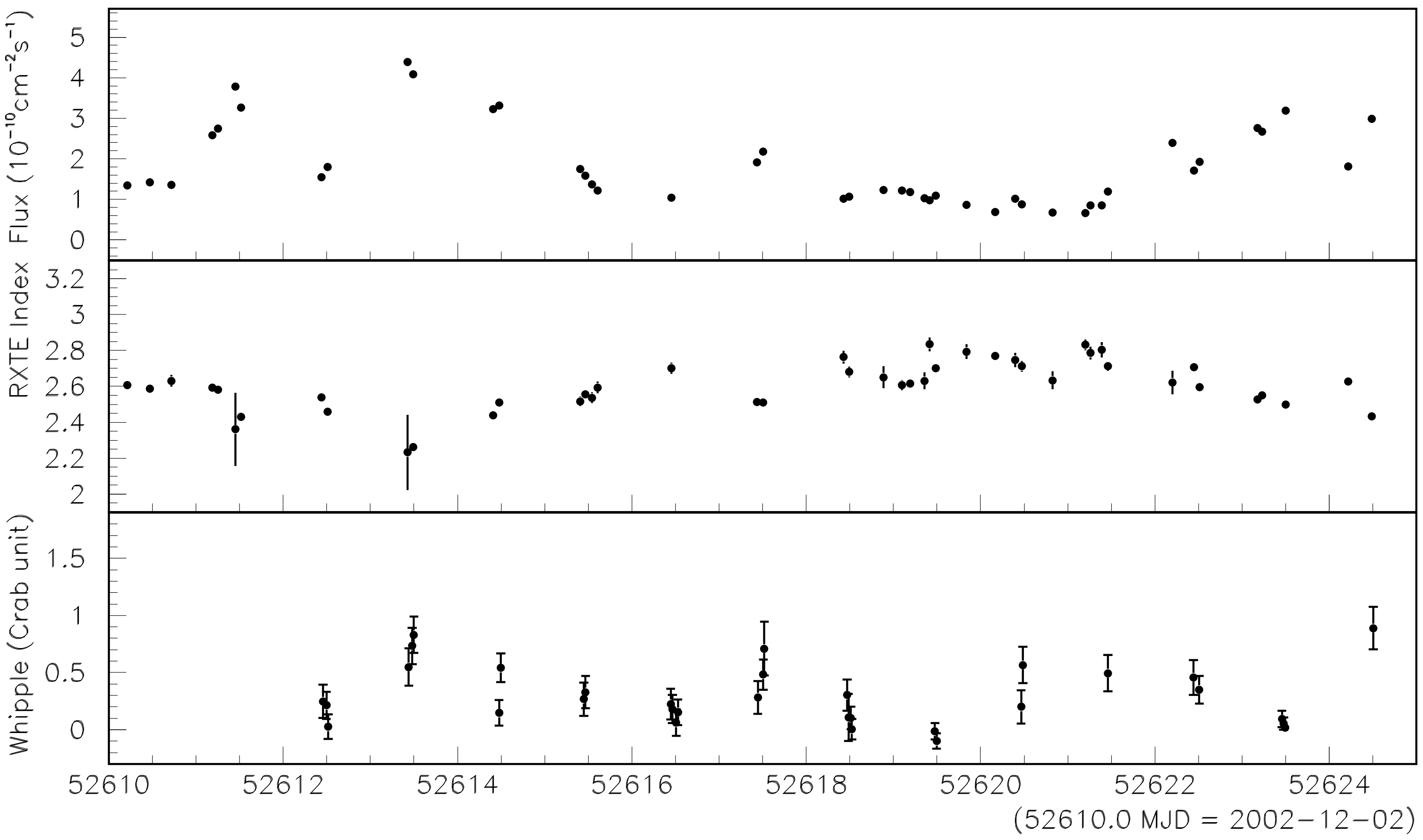
Ftools 5.3 was used for processing and extraction of PCA lightcurves and spectral data. Only PCU0 and PCU2 counters were operation during every epoch, and are used here. Log-parabolic fits yielded smaller χ-squared values than powerlaw and cutoff powerlaw fits, however simple powerlaw fits are given as a preliminary step due to the steep spectrum over the RXTE-PCA 3 - 15 keV.

Lightcurves

RXTE Campaign
PI: H. Krawczynski
Obs: P70161

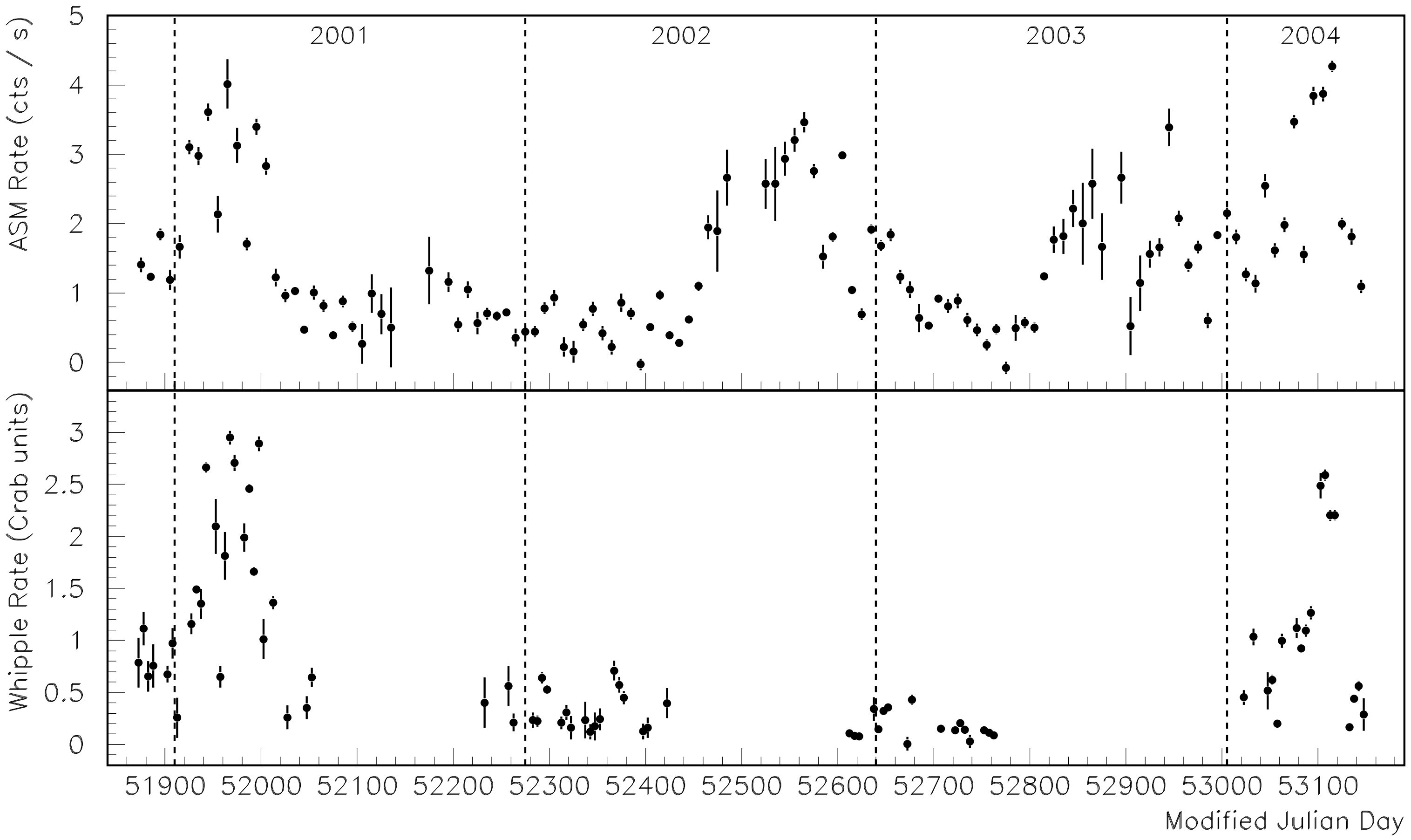
Spectral index evolves with flux state

Quiescent flux level caught after flaring state in ASM



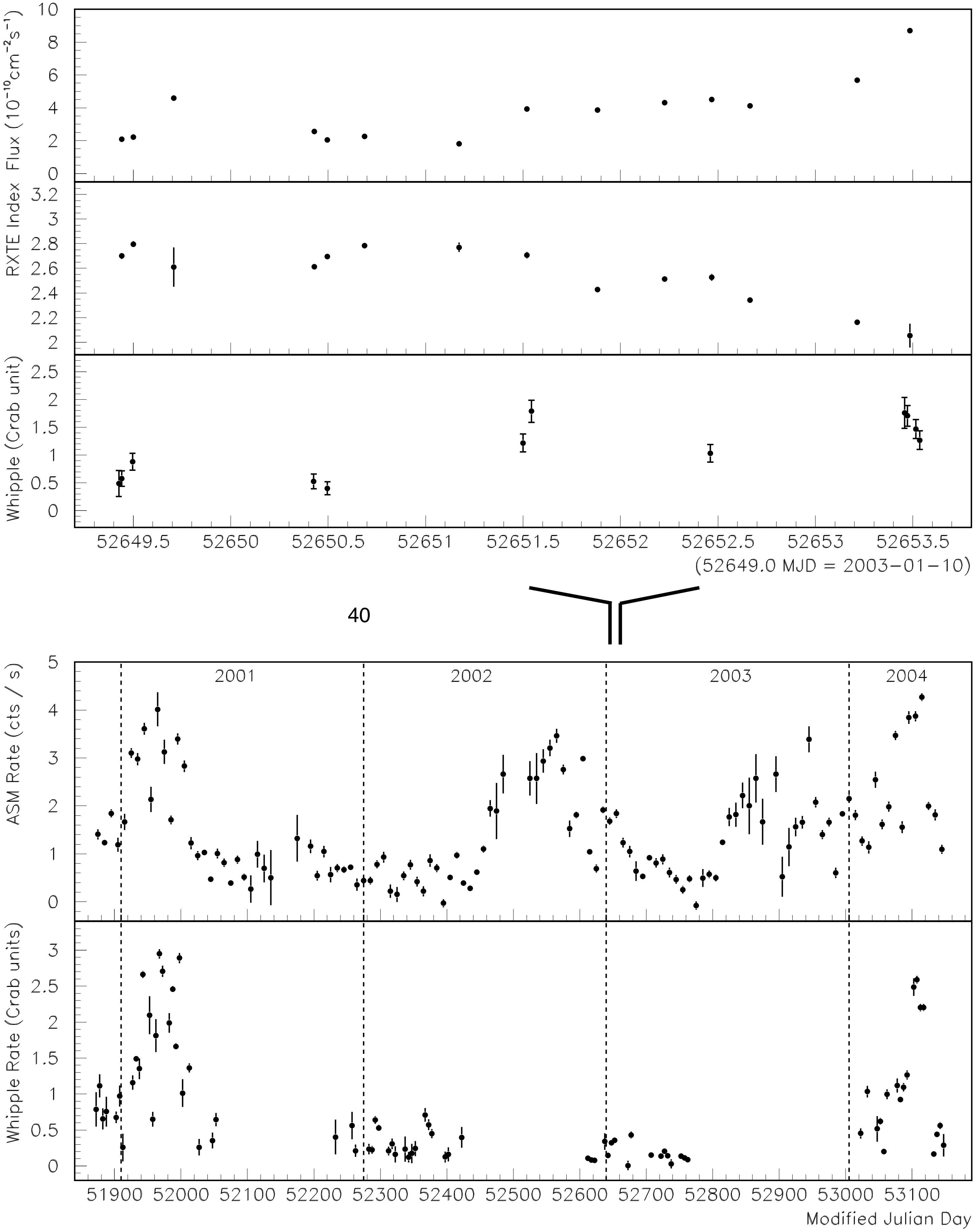
Long-term Variability:

Strong, correlated variability on monthly timescales.



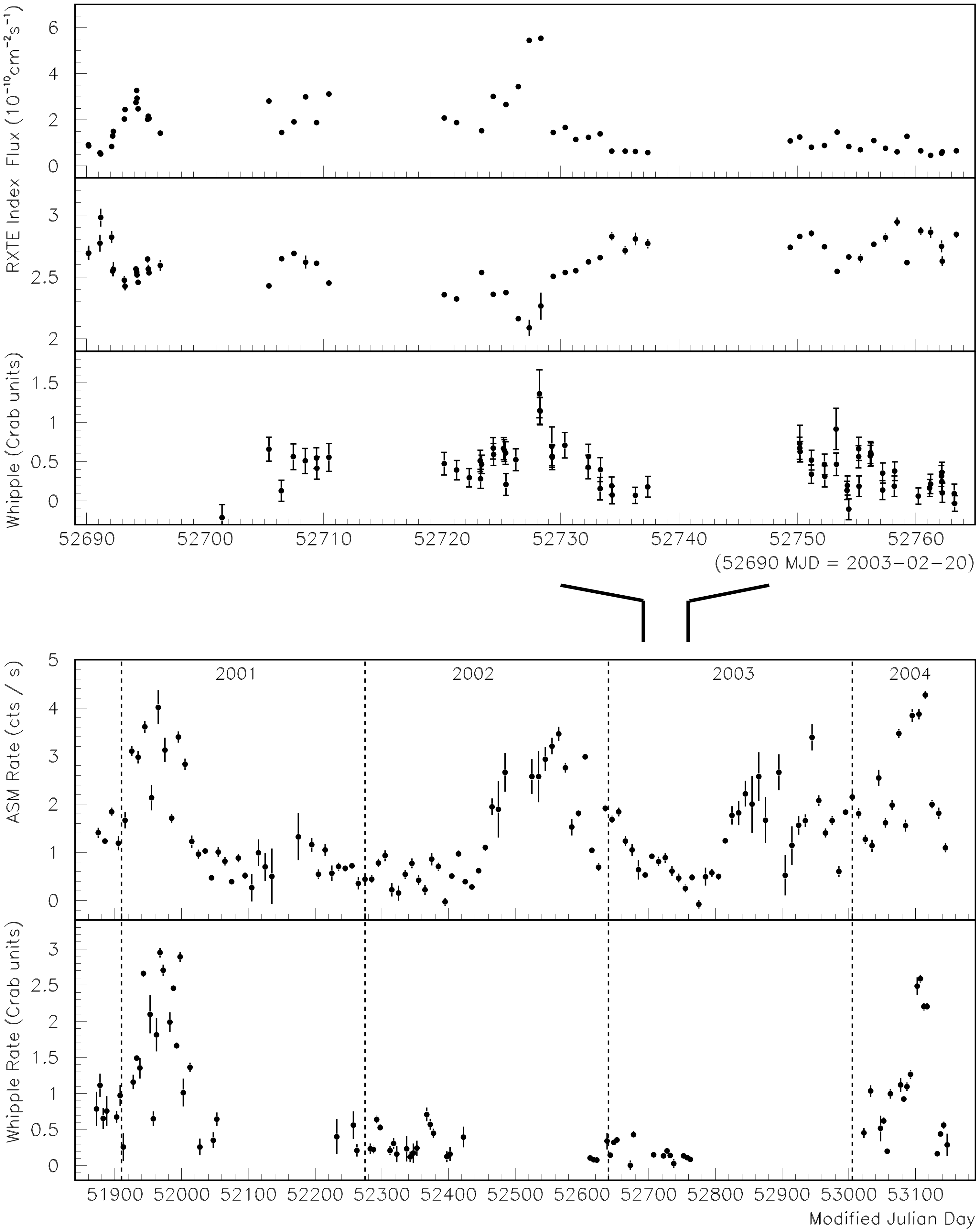
Lightcurves

RXTE Campaign
PI: H. Krawczynski
Obs: P70161



Lightcurves

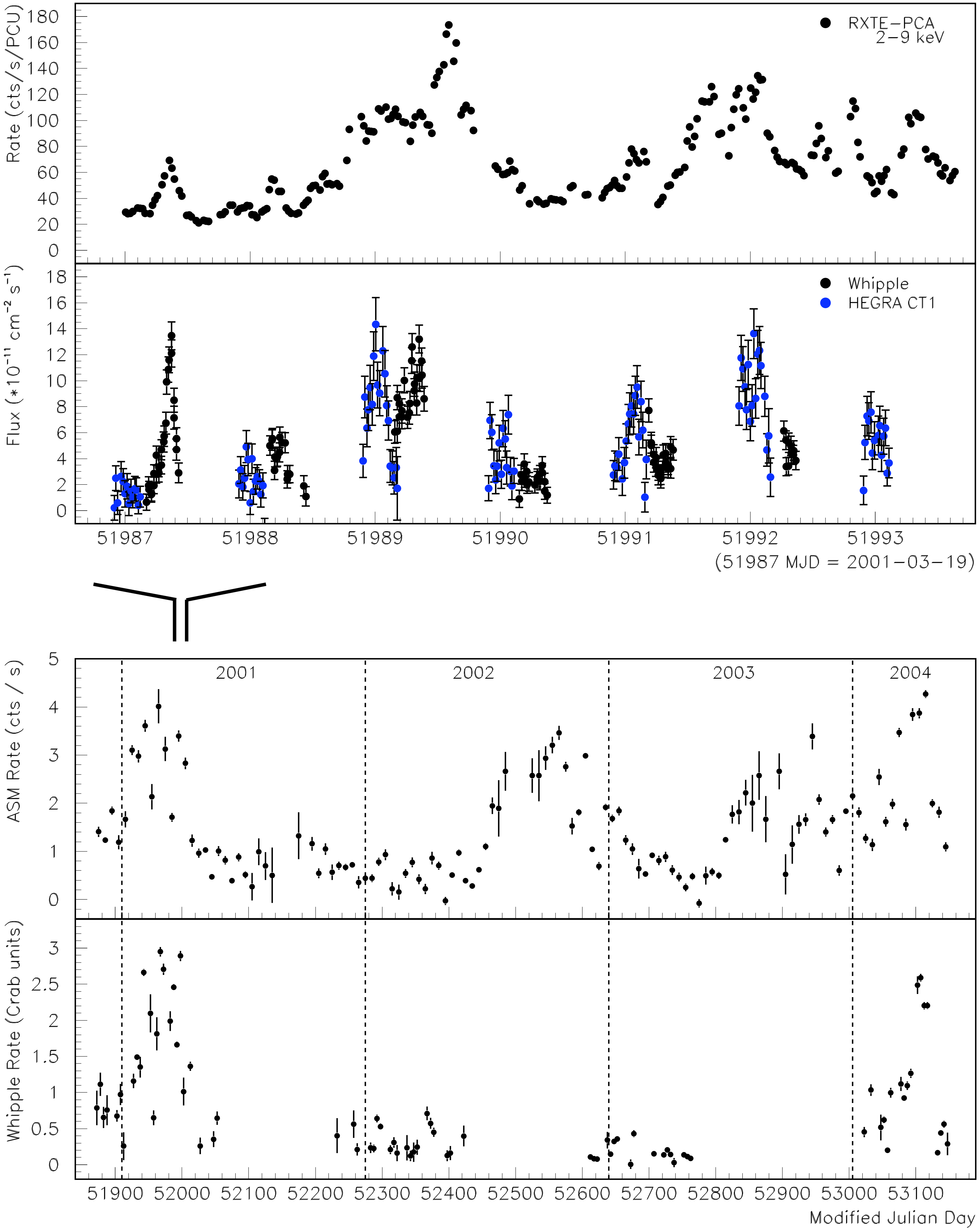
RXTE Campaign
PI: W. Cui
Obs: P80173



Lightcurves

RXTE Campaign
PI: G. Fossati
Obs: P60145

Fast Variability:
Near continuous observations show significant X-ray and TeV flaring structure on hourly timescales.

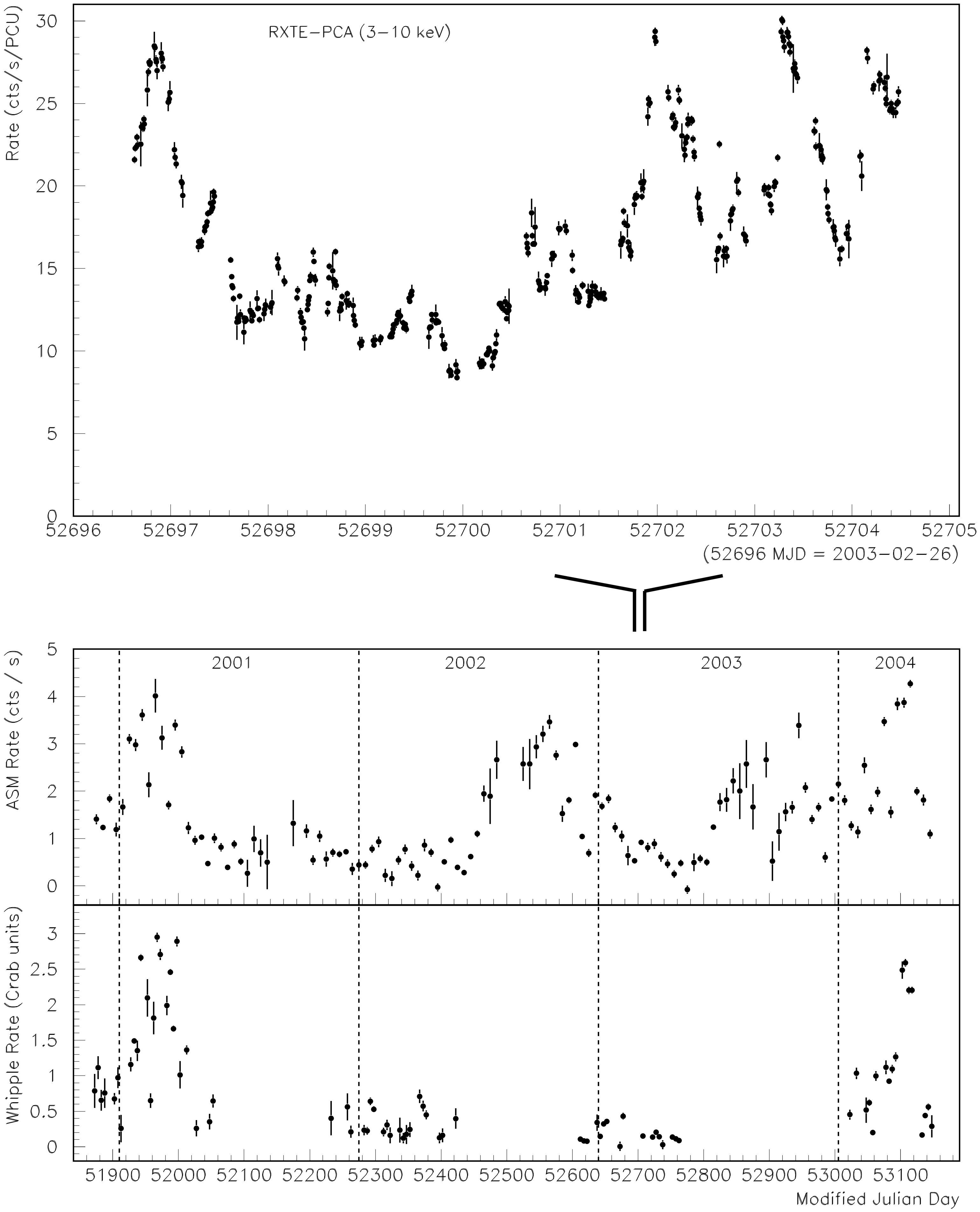


Lightcurves

RXTE Campaign
PI: R. Edelson
Obs: P80172

Fast Variability:

Well-resolved X-ray flaring structure similar to high state flux level. Due to bad weather, no Whipple 10m data was taken.



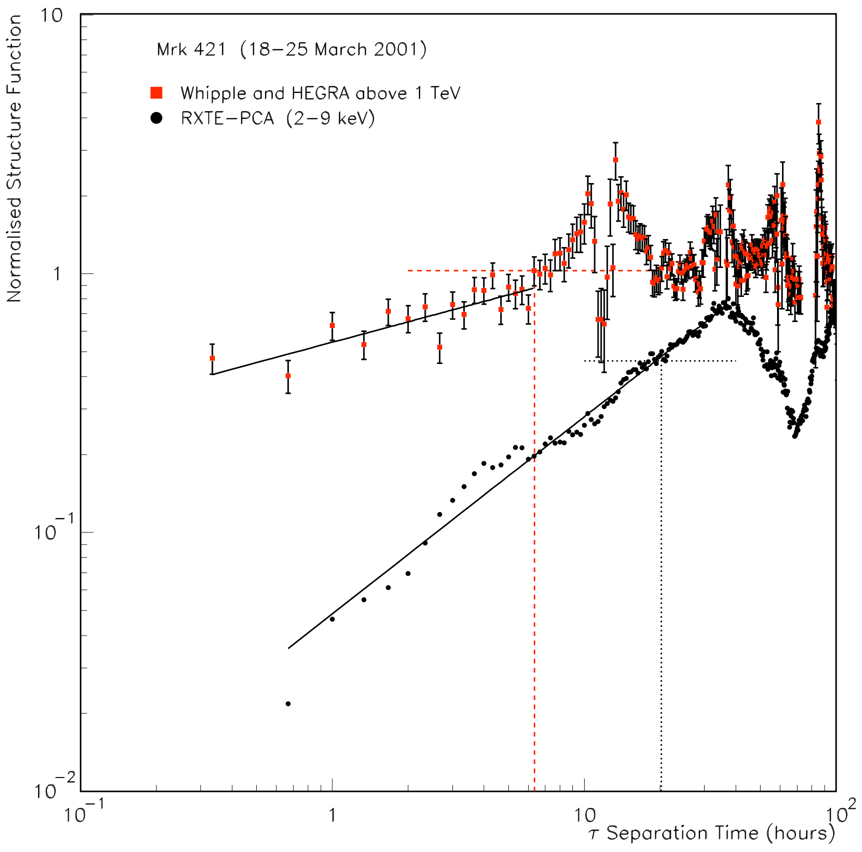
Structure Function Timing Analysis

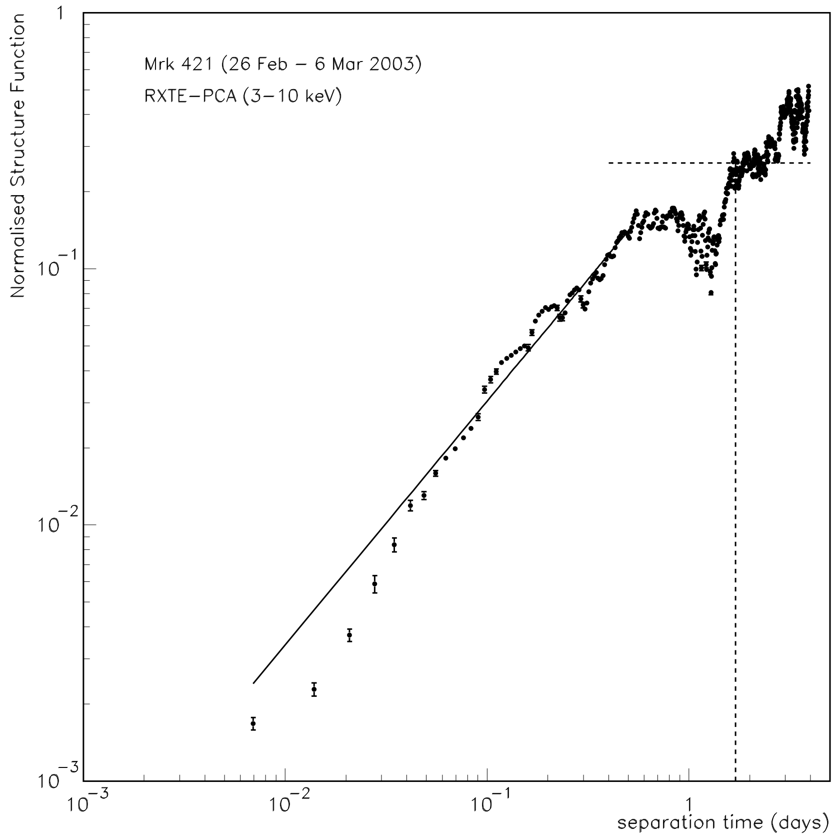
$$SF(\tau) = \frac{1}{N_P} \sum [a(t) - a(t+\tau)]^2$$

One can estimate the characteristic variability in the X-ray and TeV bands as a break in the SF from a powerlaw-like rise to a plateau where points with a certain lag are no longer correlated.

SF analysis verifies the shorter correlation timescales at TeV energies of ~7 hr to an X-ray timescale of ~20 hr. A steep rising slope (β ~1) is evident of correlated variability on timescales down to the binned duration (20 min) alluding to a superposition of many smaller flares seen in the overall lightcurve.

Large flares in the 2003 lightcurve produce a misleading continually rising SF. Normalizing with a running mean may help. Simulated lightcurves are needed to test SF analysis.





Conclusion

Long-term lightcurves from 2000 - 2004 display large amplitude variations in flux state, and a temporal guide for clarifying future spectral evolution studies.

Simultaneous absorption corrected TeV spectral measurements over the quiescent and flaring observations could allow detailed modeling of long-term flaring levels.

The true pile-up flaring nature is best probed with spectral measurements on the hour timescales given by structure function analysis.

The increased sensitivity of "next-generation" IACT (VERITAS, HESS, Magic, and Cangaroo-III) coupled with multiwavelength observations in the X-ray (Astro-E2) and GeV (GLAST) bands will greatly expand our understanding of TeV blazars.