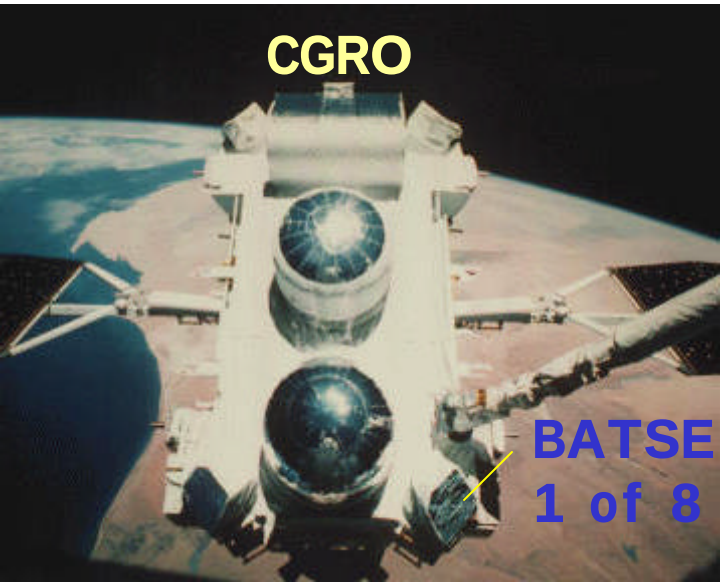
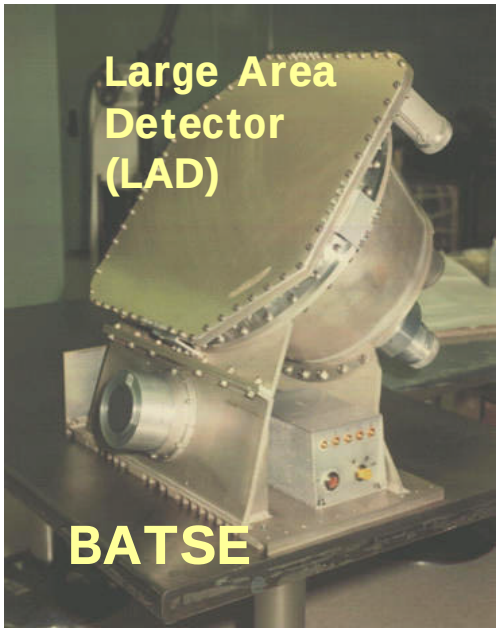
9.1 Years of All-Sky Hard X-ray Monitoring with BATSE





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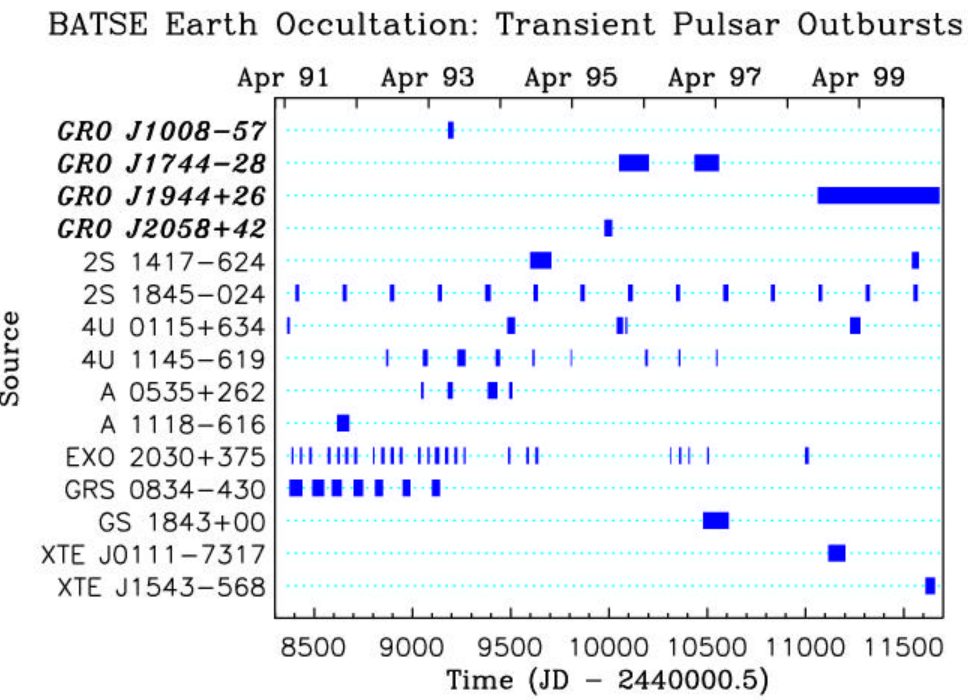
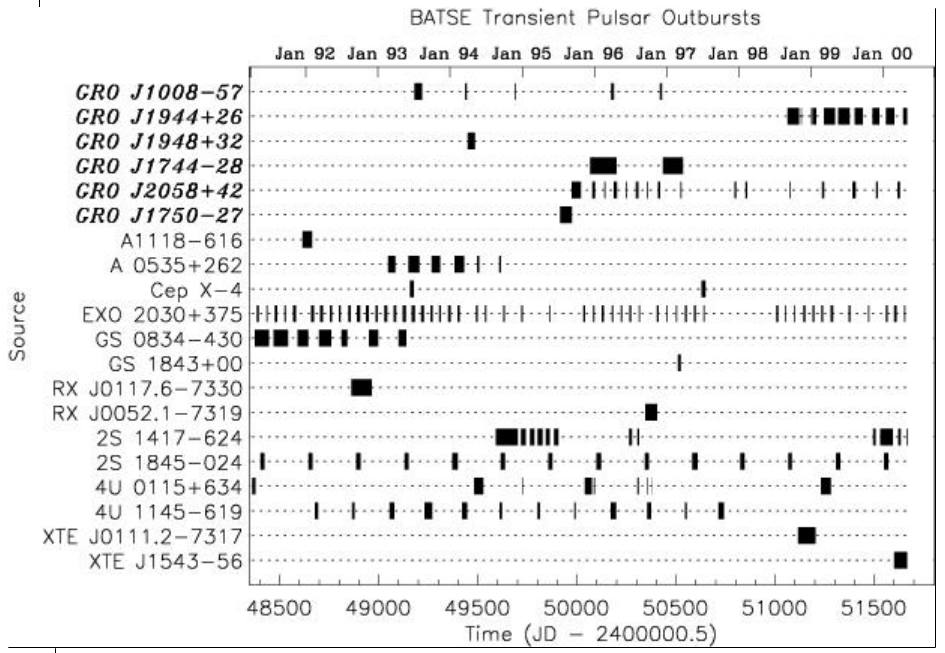
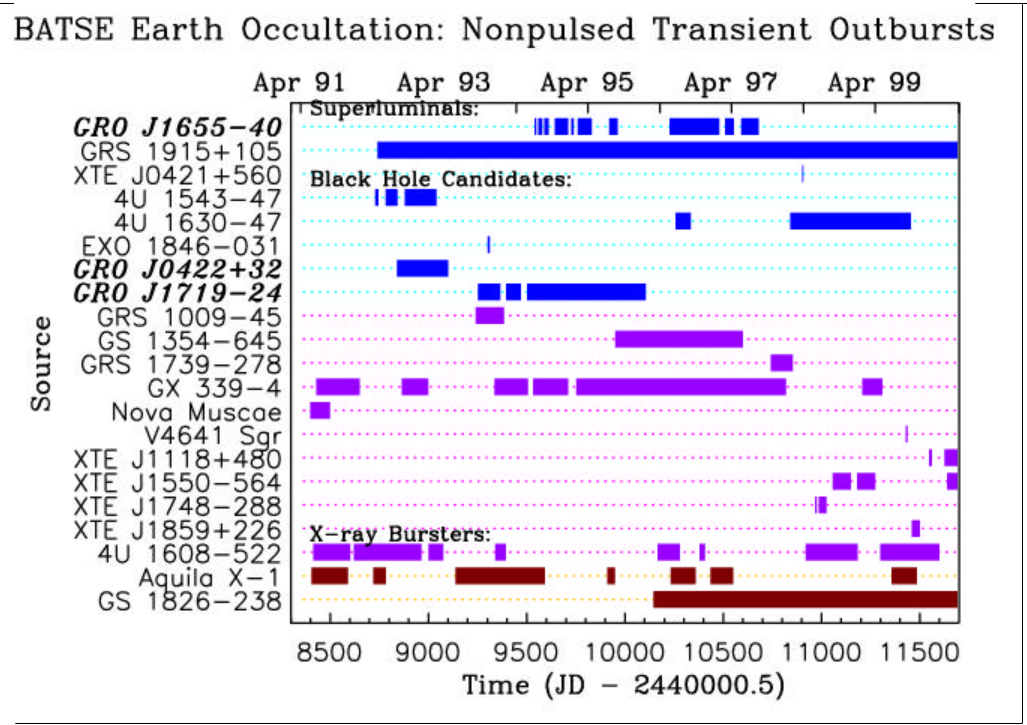
Abstract

The hard X-ray sky was continuously monitored with the BATSE experiment on the Compton Gamma Ray Observatory using the Earth Occultation method. Known sources were monitored twice every orbit and transients could be detected at about the ~50 mCrab level on a daily basis. Long-term, post-processing of the complete BATSE dataset will produce all-sky, hard X-ray maps at a sensitivity level of ~5 mCrab in un-crowded regions. For long period pulsars (>1 second), Fourier transforms and epoch-folded searches were used to measure pulse frequency and pulsed flux. Using these methods, 3 black hole candidates and 6 X-ray pulsars were discovered with BATSE during its 9 years in orbit. I will present highlights from BATSE observations of X-ray binaries from 9 years of monitoring the hard X-ray sky.

BATSE = Burst and Transient Source Experiment





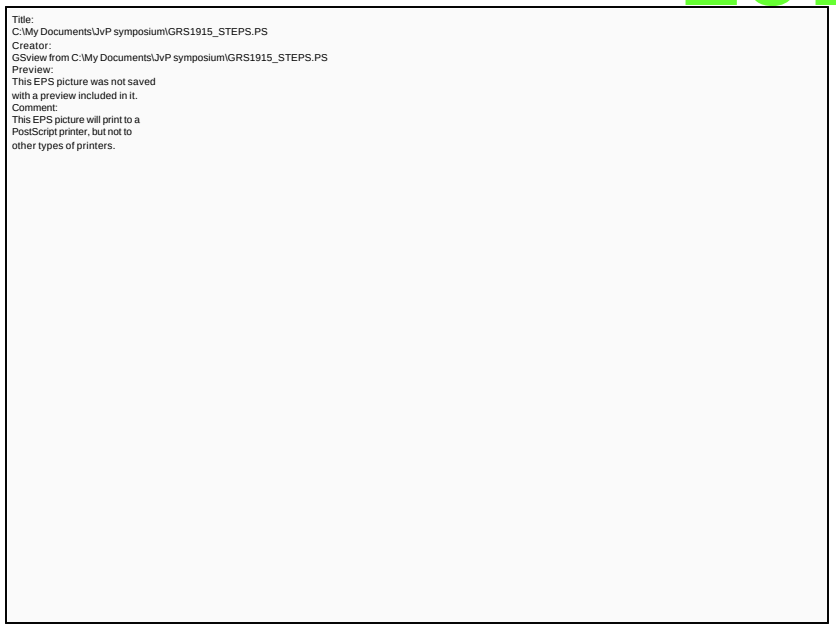


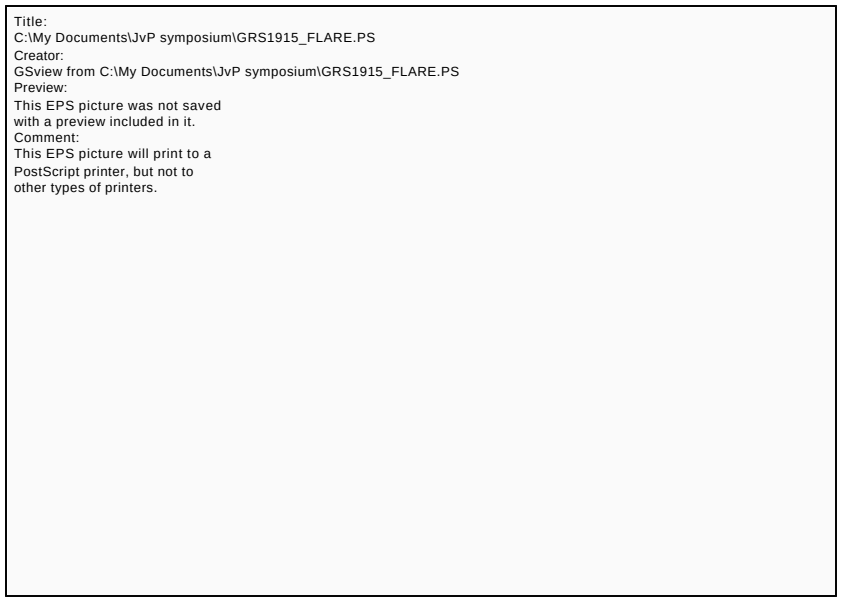
BATSE observed a number of transient X-ray binaries, via Earth Occultation (left) and pulsed frequency searches (above). Many objects had recurrent outbursts.

Earth Occultation Technique

- **Occultation steps for a given source occurred twice per 90 minute CGRO orbit.**
- **Standard Technique**
  - *Occultation step times were computed based on CGRO and source locations.*
  - *For each step, a 220-s window of BATSE 16-energy channel, 20 keV-1 MeV, data centered on the occultation of a source was fitted with a quadratic background and terms for the source and any interfering sources.*
  - *Measurements were averaged over typically days to weeks to obtain detections.*
  - *3 new black hole candidates were discovered with BATSE.*
- **A catalog of 180 sources, consisting of mostly X-ray binaries, was monitored.**
  - *82 sources were detected at >10σ with average fluxes >5 mCrab (20-100 keV) or confirmed outbursts.*
  - *36 additional sources were detected at 3-10σ.*

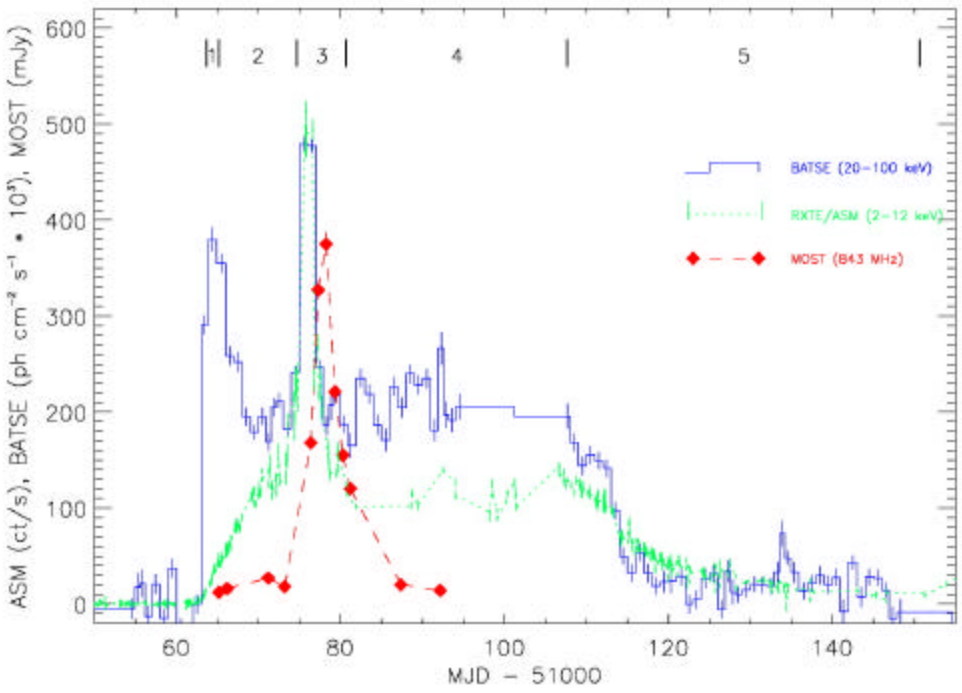
Earth Occultation Highlights: GRS 1915+105





- **GRS 1915+105 is a microquasar discovered with GRANAT/Watch in June 1992.**
- **In May 1992, a month earlier, BATSE detected bright flares from GRS 1915+105**
  - ***Seen as single occultation steps with intensities as large as 6 times the maximum flux seen since June 1992 (top).***
  - ***A close-up of flares on May 15, 1992 (bottom panel).***
  - ***These flares occurred every 20-30 minutes, similar to radio oscillations observed in September 1995.***
- **From Paciesas et al. 1996, A&AS, 120, C205.**

Earth Occultation Highlights: XTE J1550-564



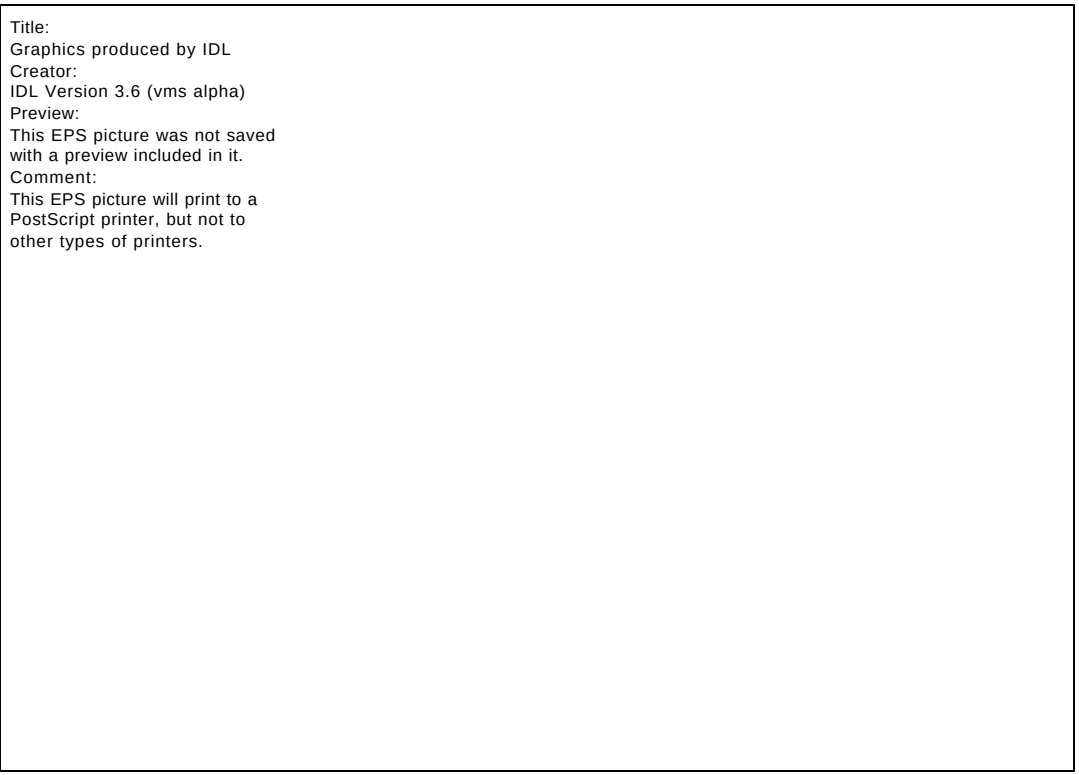
X-ray and Radio light curves of XTE J1550-564 (Fig 1b in Wu et al. 2002, ApJ, 565, 1161)

- XTE J1550-564 is a black hole candidate.
- The hard X-ray outburst rose abruptly to a flux level of about 1 Crab (20-100 keV) in 1 day, while soft X-rays (2-10 keV) rose much more slowly.
- The initial hard X-ray spike was believed due to transfer of low angular momentum material onto the black hole.
- The rise in soft X-rays was attributed to accretion disk formation.
- The peak in soft X-rays accompanied a second peak in hard X-rays and a radio flare.
- The flare occurred when the high and low angular momentum accretion flows met.

Pulsar Monitoring 20-50 keV

- **Standard technique**
  - *Described in Bildsten et al. 1997, ApJS, 113,367*
  - *Grid search in pulsed frequency.*
  - *Produced histories of pulse frequency and pulsed flux.*
  - *38 pulsars monitored, 18 detected*
  - *Resulted in the discovery of 6 new pulsars.*
- **Improvements to the standard technique**
  - *Reduced systematic errors, resulting from aperiodic noise, Earth occultations, and harmonics from bright pulsars such as Vela X-1*
  - *Increased sensitivity through searches of longer time intervals in a grid of frequency and frequency derivatives.*
  - *Currently reprocessing BATSE data*
  - *Already resulted in detection of 3 additional pulsars and numerous additional outbursts.*

Pulsar Monitoring Highlight: EXO 2030+375



(a) Infrared K-band magnitudes
(b) 20-50 keV pulsed flux
(c) Spin frequency
(d) Orbital phase of outburst peaks
(Wilson et al. 2002, ApJ, 570, 287)

- EXO 2030+375 is a Be/X-ray binary.
- Infrared K-magnitudes indicated a decline in the density of the excretion disk around the Be star.
- A drop in X-ray flux and a change in global trend accompanied the disk's decline, confirming that the amount of material available for accretion had dropped.
- The orbital phase of the transient outbursts shifted in 1995, accompanied by a change in the Hα profile, indicating the presence of a global one-armed oscillation in the Be disk.

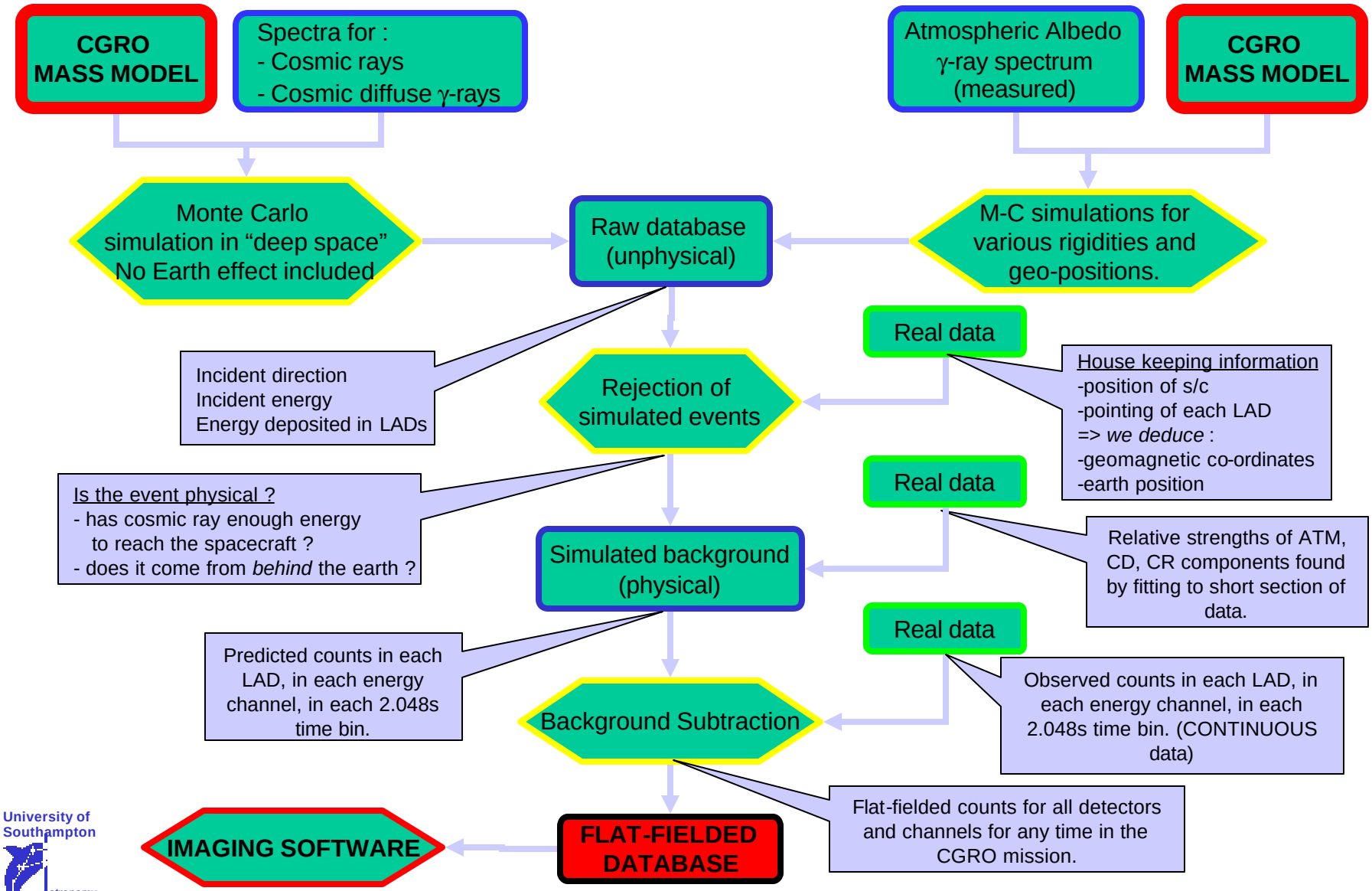
Maximum Likelihood Imaging

A Maximum Likelihood Imaging Technique has been developed by Simon Shaw at Southampton and by Jurgen Knodleseder, CESR, to produce all-sky images using Earth occultations.

- **Flat-field the data (subtract background)**
  - *GEANT 3 background model contains cosmic ray, cosmic diffuse g rays, and atmospheric g rays*
  - *Reduces systematic errors in images*
- **Use a differential filter**
  - *Converts occultation steps to peaks*
  - *Simplifies handling of data gaps*
- **Fit response vector to count rate data**
  - *Gets source strength vs. sky location*

No limit to size of map – All-sky images
Maps for short time intervals can be added together

Flat-fielded Data Production



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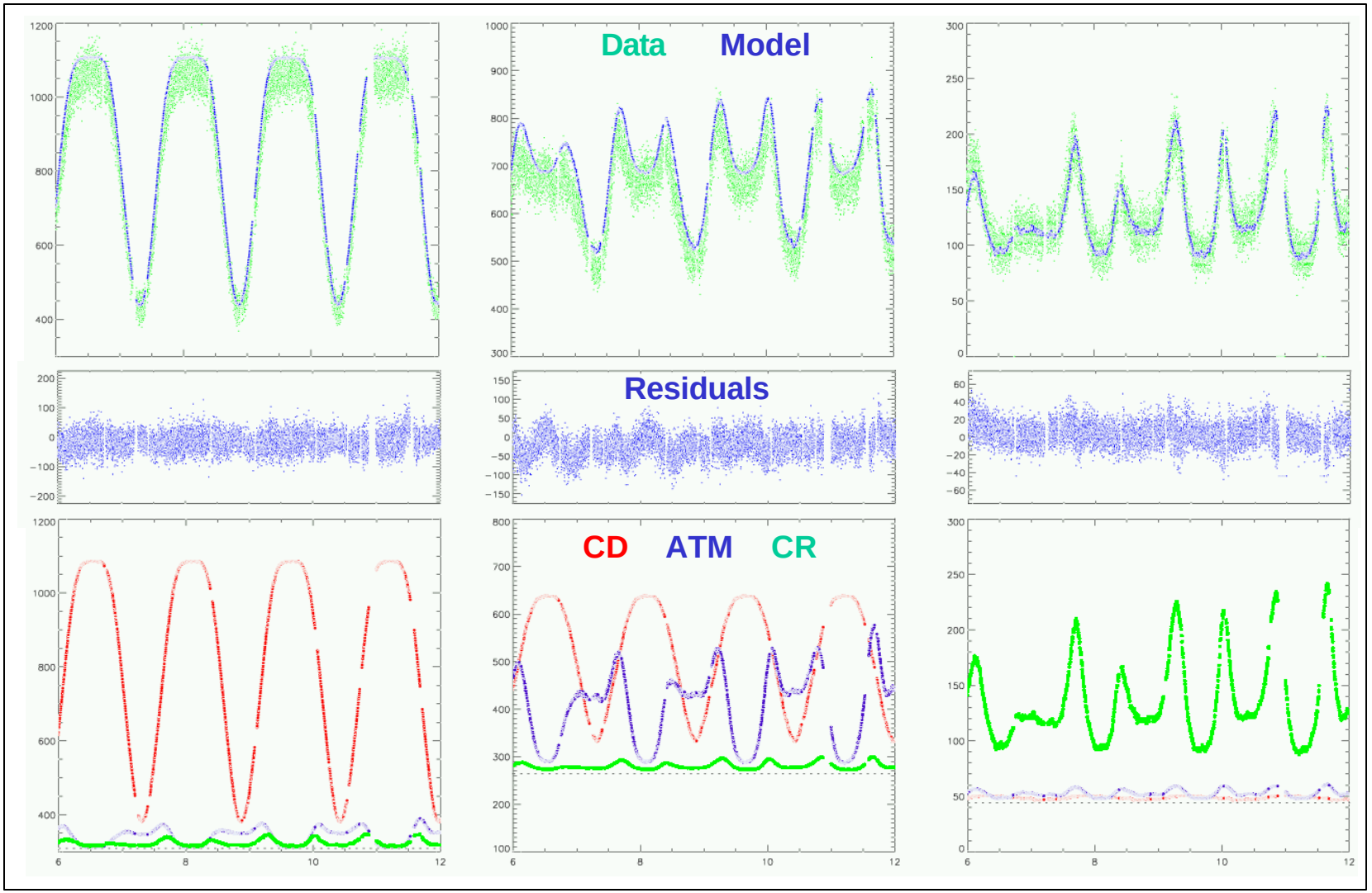
Example of Flat-fielding



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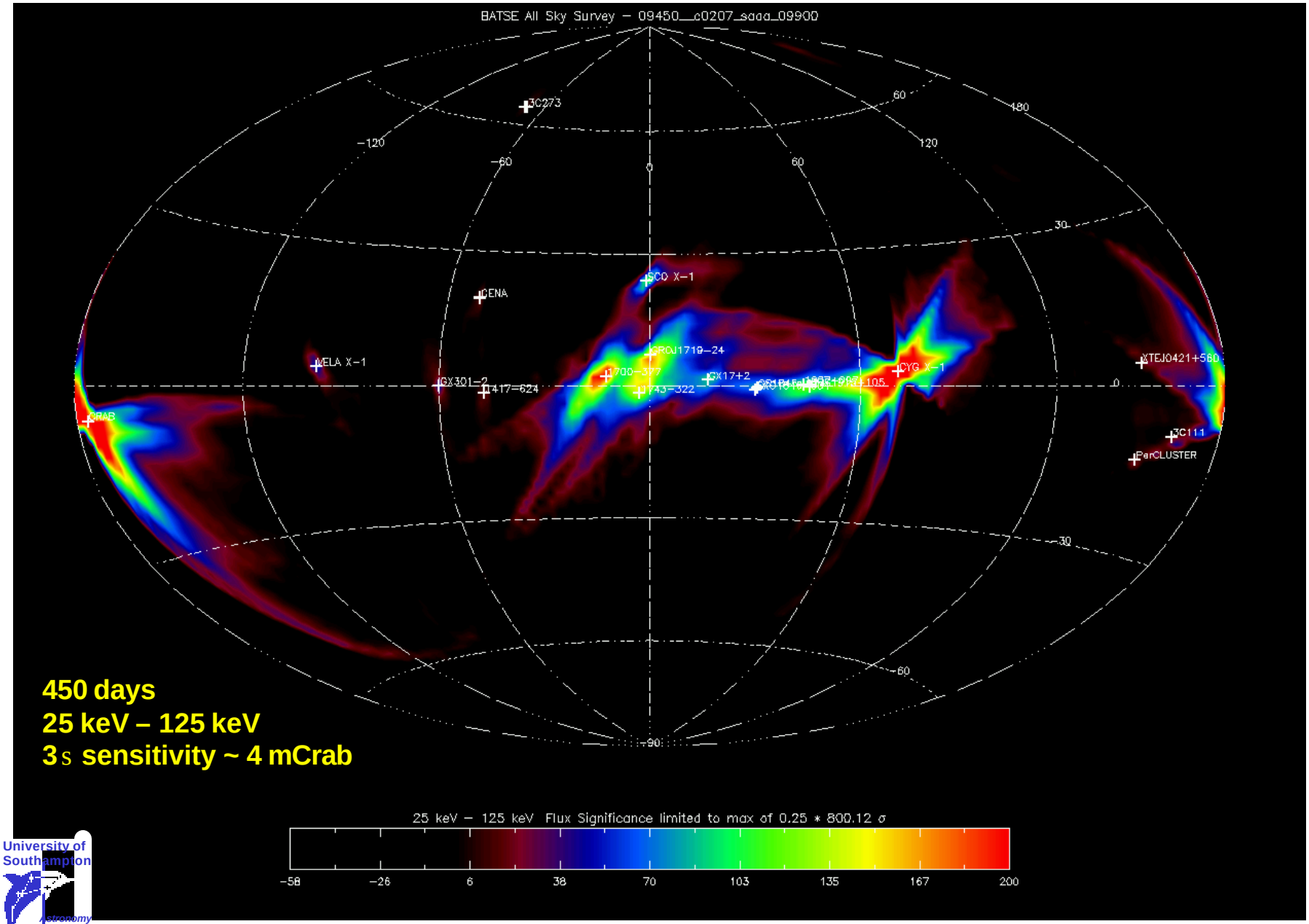
Flat - fielded Image



450 days
25 keV – 125 keV
3 s sensitivity ~ 4 mCrab

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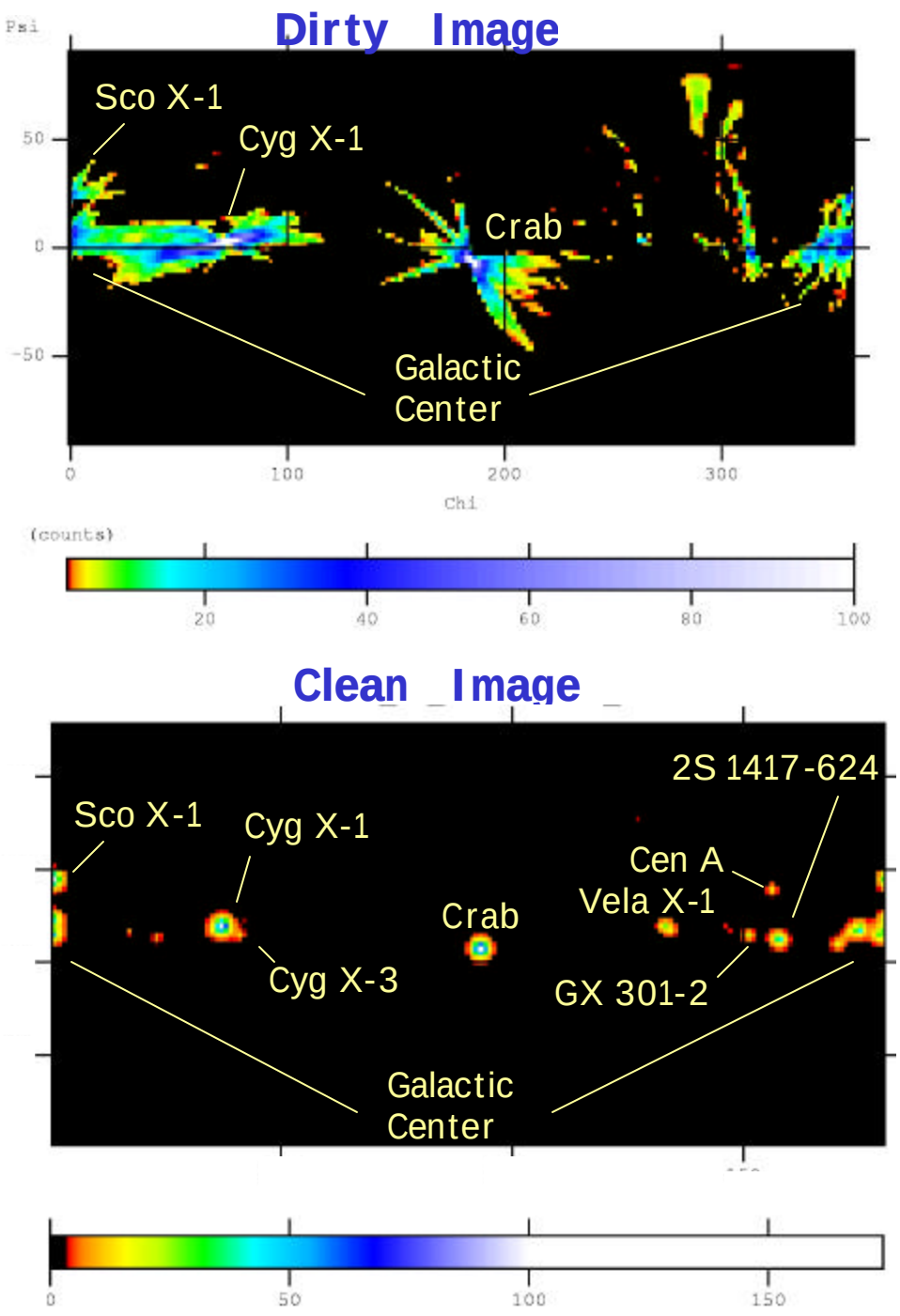
Image Cleaning

- Developer - M. Westmore (Southampton).
- Artifacts in “dirty” image are due to projections of the Earth’s limb.
- Image cleaning procedure.
  - *Generate limb pattern for most significant peak location.*
  - *Remove a small fraction of flux times limb pattern from dirty map.*
  - *Add flux removed times Gaussian point spread function to clean map.*
  - *Repeat until largest peak is below a chosen significance.*
  - *Add residual noise map to clean map.*



Expected Results of the BATSE All-Sky Imaging Survey

- Unbiased survey.
- First low-energy gamma ray all-sky survey since HEAO-A4.
- First ever all-sky survey in 300 keV-1 MeV band.
- Integral survey will continue coverage.
- Flux sensitivity 1-2 mCrab for 9 years of data.
- Location accuracy <0.1° for some sources.
- Angular resolution 0.5-2.0°.
- Likely to detect additional sources.

Summary

- BATSE provided long-term coverage of X-ray binaries for 9.1 years in the 20 keV-1MeV band.
- Integral will continue hard X-ray coverage.
- Reprocessing of BATSE data for occultation images and pulse frequency searches will likely result in detections of additional outbursts and additional X-ray binaries.
- Combined with the RXTE ASM, BATSE provides a context in which Chandra and XMM observations can be understood in relation to long-term source activity.
- Chandra and XMM observations can provide precise locations and information about the current state of X-ray binaries observed with BATSE.