Astronomical Data Analysis Software and Systems IX
ASP Conference Series, Vol. 216, 2000
N. Manset, C. Veillet, and D. Crabtree, eds.

The Earth Occultation Technique with the Burst and Transient Source Experiment

C. A. Wilson, B. A. Harmon, M. L. McCollough [1], G. J. Fishman, S. N. Zhang[2], W. S. Paciesas[2]

SD 50 Space Science Department, NASA/MSFC, Huntsville, AL 35812

Abstract. The Burst and Transient Source Experiment (BATSE) on the *Compton Gamma Ray Observatory (CGRO)* is successfully being used as an all-sky hard X-ray monitor. The experiment consists of a set of eight uncollimated detectors sensitive to photons in the 20 keV to 2 MeV range. Since *CGRO* orbits the Earth at an altitude of about 450 km, about 33% of the sky, as viewed with BATSE, is covered by the Earth at any given time. The entire sky is subject to Earth occultation for some portion of *CGRO*'s 52 day precession period. When a source sets below or rises above the Earth's limb, atmospheric attenuation produces step-like features in the BATSE data. The observed change in count rate in several energy bands provides a measurement of the source intensity and spectrum without sophisticated background models. These occultation features are used to locate and monitor astrophysical sources with BATSE when the source signal can be separated from the detector background. Examples of step searches, spectra, light curves, and transform imaging are presented.

1. Introduction

Most all-sky monitors have been limited to the soft X-ray range (1-12 keV), but high energy emission from objects such as X-ray binaries, pulsars, and active galaxies extends well above 10 keV due to Compton scattering of soft photons with energetic particles, synchrotron radiation, pair production, pion decay, and Bremsstrahlung processes. The Burst and Transient Source Experiment (BATSE) on the *Compton Gamma Ray Observatory (CGRO)* is being used as an all-sky monitor of point-like hard X and γ ray sources in the 20 keV-1 MeV energy range (Harmon et al. 1993). Since BATSE is not a pointed instrument, Earth occultation features are used to locate and monitor astrophysical sources. When a source goes behind (or emerges from behind) the Earth, step-like features are produced in the BATSE data twice every 90 min orbit. These "occultation steps" are used to measure source fluxes and energy spectra and to locate new sources. Example occultation steps are shown in Figure 1.

[1]Universities Space Research Association

[2]University of Alabama in Huntsville

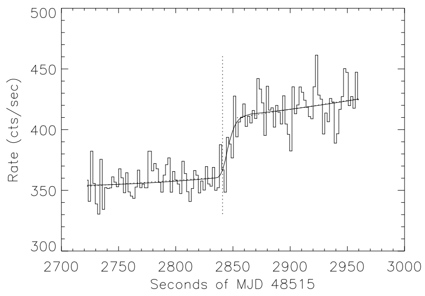

Figure 1. Example of rising and setting Earth occultation steps from the Crab Nebula in BATSE CONT Channel 1 (20-30 keV) data, denoted by the histogram. The solid line is the step model fit and the vertical line is the predicted step time for the Crab Nebula.

2. Instrument

BATSE consists of eight identical uncollimated detector modules positioned on the corners of the *CGRO* spacecraft such that the normal vectors of the detectors are perpendicular to the faces of a regular octahedron, providing all-sky coverage. The BATSE analyses presented here use the large-area detectors (LADs), which are NaI(Tl) scintillation crystals with a geometric area of 2025 cm^2 and a thickness of 1.27 cm. The LADs are sensitive to photons from 20 keV to 2 MeV. Two BATSE data types are used in these analyses, the CONT (2.048 s, 16 energy channel) data and the DISCLA (1.024 s, 4 energy channel) data. A more complete description of the instrument and data types can be found in Fishman et al. (1989).

3. Observational Techniques

3.1. Step Fitting

The intensity of a known source is measured with BATSE by computing the difference in total count rate in source facing detectors just before and after Earth occultation. Typically about two minutes of data (fitted separately in each energy channel and in each detector) immediately before and after an occultation step are fitted with a quadratic background and source terms:

$$\lambda(t) = \sum_{j=0}^{2} b_j (t - t_{\rm occ})^j + \sum_{n=1}^{N} s_n T_n(t) \tag{1}$$

where $\lambda(t)$ is the time-dependent model count rate, b_j is a background coefficient, and $t_{\rm occ}$ is the predicted occultation time when the line-of-sight vector from the spacecraft to the source reaches an altitude of 70 km above the Earth's surface, which corresponds to 50% attenuation of 100 keV photons. For each of n fitted sources, s_n is the source intensity in counts s^{-1} and $T_n(t)$ is the atmospheric transmission function, a time-dependent step-like function defined by the atmospheric attenuation along the line of sight to that source, i.e.,

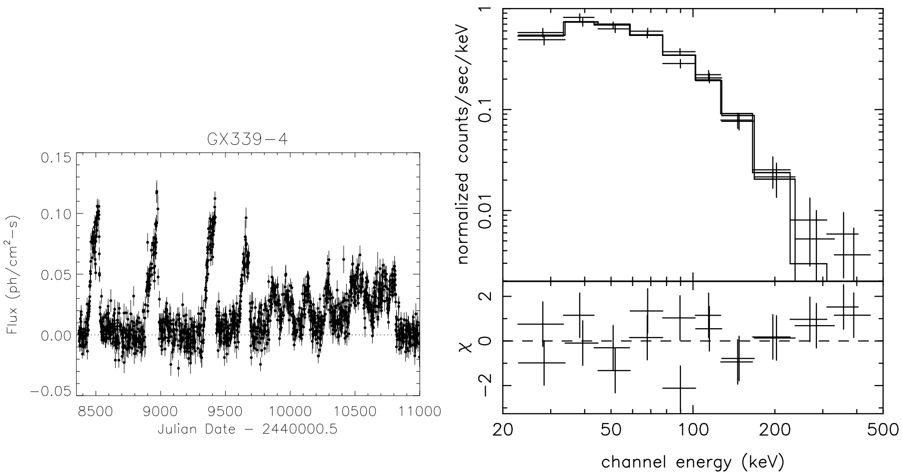

Figure 2. (*Left*):Average daily photon flux from GX 339-4 measured with BATSE Earth occultation in the 20-100 keV band from April 1991 to July 1998. (*Right*):Count spectrum and fit residuals measured with BATSE for GX 339-4.

$T_n(t) = \exp\{-\mu(E)A(h(t))\}$ where $\mu(E)$ is the energy dependent mass attenuation coefficient and $A(h(t))$ is the air mass at altitude h at time t. Interfering sources are defined as known sources expected to exceed 60-100 mCrab (1 mCrab = 0.1% of the intensity of the Crab Nebula, the standard candle in X and γ ray astronomy), that are occulted within the fitting window. In practice, usable steps are not obtained twice per spacecraft orbit due to interfering sources occulting within 10 seconds of the measured source, γ ray bursts, solar flares, electron precipitation events, and South Atlantic Anomaly passages. For most sources, 10-20 clean steps per day are available. Typically, several occultation steps are averaged to obtain an intensity measurement. An average 1-day 20-100 keV sensitivity of about 100 mCrab is achieved for most source locations. Daily flux measurements are generated by convolving a simple spectral model (a power law or thermal Bremsstrahlung model) with the detector response matrices and fitting it to the observed count spectra. Detailed spectral fitting is done using BATSE software or XSPEC. Examples of a light curve and a count spectrum derived from occultation step fits are shown in Figure 2 for the black hole candidate GX 339-4.

3.2. Step Searches

A search for occultation steps from new sources is routinely performed on each day's BATSE data. Data in each LAD are first summed over the 30-200 keV range to obtain the best signal to noise for Crab-like spectra. Then a series of tests are performed on a contiguous data segment within a four minute fitting window to determine if an occultation step is present within the window. If a step is present, a fit is made to estimate the time of the occultation and the significance of the step. Once a data segment has been tested, results are logged and the window moves to the next data segment. Results are then plotted for a full day. If steps from one source are present, they will cluster in time (measured

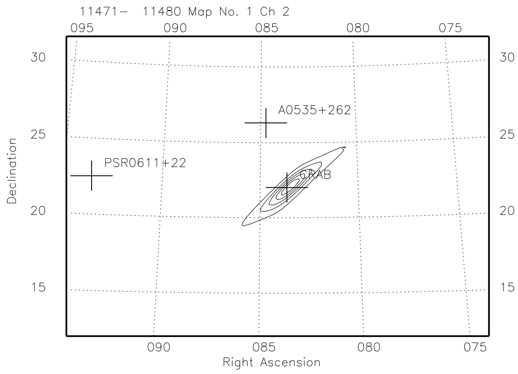

Figure 3. Example of an Earth occultation transform image centered near the Crab Nebula.

since orbit start). Clusters from known sources are identified, allowing quick localization of new transient sources.

3.3. Imaging

Occultation steps in the time domain can be transformed into spatial information for image construction (See Figure 3). This has enhanced BATSE's ability to locate and identify weaker sources and increased BATSE's effectiveness as an all-sky monitor (Zhang et al. 1995). BATSE measures the change in count rate along the arc of the Earth's limb projected onto the sky at the time of an Earth occultation. The location of the spacecraft is well known, resulting in accurate knowledge of the position and orientation of the Earth's limb projection. This effectively allows us to image one dimensional strips of the sky. As the spacecraft orbit precesses, the position and orientation of the Earth's limb projection changes, allowing us to combine one dimensional strips into a two dimensional image. A curved Radon transformation (Deans 1983) is used to describe the projection of the Earth's limb on the sky. The image is reconstructed using the Maximum Entropy Method (Huesman et al. 1977).

References

Deans, S. R. 1983, The Radon Transform and Some of Its Applications, (New York: Wiley)

Fishman, G. J., et al. 1989, in Proc. GRO Science Workshop, ed. W. N. Johnson (Greenbelt: NASA/GSFC), 2

Harmon, B. A. et al. 1993, in Compton Gamma Ray Observatory, AIP Conf. Proc. 280, eds. M. Friedlander, N. Gehrels, D. J. Macomb (New York: AIP), 314

Huesman, R. H. et al. 1977, Donner Algorithms for Reconstruction Tomography, LBL Publ. 214, 42

Zhang, S. N. et al. 1995, Exp. Astron. 6, 57