Aperture Photometry and Time Series Analysis of Selected Blazars

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Blazar LC: Time Series Analysis

- Time series analysis TSA (evolved from both signal-processing engineering and mathematical statistics) is fundamental in the study of blazar light curves (LC) and variability.

- TSA provides tools and methods able to explore and extract temporal patterns (signal features) in the light curves, to estimate characteristic timescales (the powerful scales of variations), duty cycles (the fraction of time spent in an active state), flare structure and trends, to specify the dominant modes of fluctuations and the power spectrum of the signal, to determine auto/cross-correlations and time lags, transient events, periodicity and composite modulations, scaling and coherency, oscillations and beatings, distortions and instabilities, intermittence and drifts, dissipation and dumping, long-memory patterns and self-similarity, resonance and relaxation processes, random and deterministic features, linear and non-linear processes, stationary and non-stationary activity...

- GLAST will be able to provide nice gamma-ray light curves for variable blazars in few months (first DC2 lesson learned).

From: J. McEnery 2006, ASP Conf Proc. 350, 229
DC2 Blazar Flux LCs

- DC2 blazar fluxes determined using python scripts and the standard method of aperture photometry.

1. Light curves extraction

- Source raw counts, with $E > 100$ MeV are extracted from the all sky FT1 v1 file using an aperture radius of $r = 2^\circ$.

- The background is estimated in an annulus having $r_1 = 3^\circ.5$ and $r_2 = 5^\circ.5$ and centered on the source position.

- The solid angle averaged bkg. value is then evaluated and subtracted to the signal to obtain the net source counts.

- The net source counts are divided by the exposure to obtain the flux.

3C 279 fields
Method: Aperture Photometry

2. The exposure

1. An energy weighted Effective Area is evaluated using:
   - CALDB files to get the $A_{\text{eff}}(E,\theta,\phi)$ (DC2 front and back Class-A Tables)
   - The pointing history file (FT2 v1)

\[
A(\theta, \phi) = \frac{\int_{E_1}^{E_2} E^{-2} A(E, \theta, \phi) dE}{\int_{E_1}^{E_2} E^{-2} dE}
\]

Where $\theta, \phi$ are the angles between the source direction and the LAT z-axis direction.

The exposure for a given source at $(ra, dec)$ is then calculated as

\[
\varepsilon(ra, dec) = \sum_i A(\vartheta, \phi) T_i(\vartheta, \phi)
\]

Where $T(\theta, \phi)$ is the livetime for each direction.
Sources processed: all the DC2 BL Lacs + FSRQs recognized. LC bin = 1 day

Calculated quantities: 1. the gamma-ray flux above 100 MeV (x10^{-6} phot cm^{-2} sec^{-1}) 2. counts 3. background 4. counts-back 5. exposure (s).
Some TSA methods (suitable for unevenly sampled TS) are applied to a small sample of DC2 blazars. Note: LAT blazar light curves can be unevenly sampled too, i.e. there are time bins where there is no flux detection (second DC2 lesson learned).

The first order structure function (SF) is equivalent to the power spectral density function (PSD) of the signal calculated in the time domain instead of frequency space. The SF is a measure of the mean squared flux differences \((F_i - F_{i+\Delta t})\) of N pairs with the same time separation \(\Delta t\).

\[
SF^{(1)}(\Delta t) = \frac{1}{N} \sum_{i=1}^{N} (F_i - F_{i+\Delta t})^2.
\]

The general definition involves an ensemble average.

Drops in the SF means a small variance and are signatures of possible characteristic timescales.

Typically SF increases with \(\Delta t\) in a log-log plot showing an intermediate steep curve, whose slope \(b\) is related to the power law index \(a\) of the PSD by \(a=1+b\). A typical PSD has indeed a power-law dependence \(P(f) \propto 1/f^a\) on the signal frequency \(f=1/t\) in a large range of values.

If a LC reaches a maximum correlation timescale, SF is constant for longer lags (the turnover point identify another characteristic time scale).

If there is under-sampling SF shows a wiggling pattern and fake breaks that can provide fake scales.
The periodogram is analogous to the Fourier analysis for discrete unevenly sampled TS, useful to detect the strength of harmonic components with a certain angular frequency.

Wavelets are used to transform a signal into another representation able to showing the information in a more useful shape. It is a useful tool especially to detect and identify signals with exotic spectral features, transient information content, and non-stationary properties.

The wavelet transform WT allow a local decomposition of the scaling behavior in time for each quantity (in contrast to the usual methods based on the Fourier analysis), allowing the signal features and the frequency of their "scales" to be determined simultaneously. Wavelets are localized (in both space and pulse spaces), oscillatory functions whose properties are more attractive than sine and cosine functions.

WT is computed at different times in the signal, using mother wavelets (here we used the Morlet complex-valued waveform) of different frequency and convolved on each occasion. The WT power spectrum (i.e. the modulus of the transform value) on a two dimensional location-frequency plane is obtained (the so called wavelet "scalogram").
DC2 Blazar Flux LCs

The famous and gamma-ray loud blazar 3C 279

Sub-day binned LCs can be obtained and hours variations can be detected for the brightest gamma-ray blazars (third DC2 lesson learned).
A possible $15/16$ day characteristic timescale found in the 3C 279 DC2 integrated light curve above 100 MeV (a drop and slope change at $\Delta t = 15$ days in the SF).

Standard TSA method can be well applied to LAT blazar light curves and providing useful information (fourth DC2 lesson learned).
This 15/16 days scale appear to be confirmed by the periodogram (a peak in both the 1-day bin and 8h-bin power plots) and the Wavelet scalogram (another peak). Anyway the wavelet plot warn about edge effects (these are important in the cross-hatched region). The thick black contours are the 90% confidence levels of true signal features against white/red noise background spectrum.
PKS 0735+178 (3EG J0737+1721): show an isolated flare and no typical timescales (but a possible SF flattening around 25 days is hinted).
DC2: Mkn 421 & 3C 66A

Mkn 421 flux light curve

3C 66A flux light curve

Mkn 421

3C 66A

Mkn 421

3C 66A

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DC2 Closeour Meeting - GSFC May 31-June 2 2006
Summary on the DC2 blazar TSA.

- **1st DC2 lesson learned**: GLAST will be able to provide nice LAT light curves for variable blazars in few months.

- **2nd DC2 lesson learned**: TSA methods (suitable for unevenly sampled TS) are needed (especially if faint sources or LC in selected energy bins are used).

- **3rd DC2 lesson learned**: sub-day binned LCs can be obtained. Intra-day (hours) variations can be detected for the brightest gamma-ray blazars.

- **4th DC2 lesson learned**: standard TSA method can be well applied to LAT blazar light curves providing useful information.

- **5th DC2 lesson learned**: daily binned LC can be easily obtained for the majority of blazars. Variability on timescales > 1 day can be well investigated. These are the usual scales (days-weeks-months-years) sampled with optical monitoring observations (radio: less sampled) in some bright blazars. What we learn from optical monitoring can be useful for the next GLAST all-sky-scan monitoring of gamma-ray blazars.