Probing the Physics of Gamma-Ray Blazars with Single-Dish Monitoring Data

M.F. Aller, P.A. Hughes & H.D. Aller (U. Michigan)

The γ-ray AGN distribution: from the 11 month catalogue

Abdo et al. 2010
Outline

♣ Early results: the EGRET era

♣ Uses of Single Dish data in understanding Fermi photon flux data (light curves):
  localization of the emission site
  specification of the emission process
  exploration of the role of shocks

♣ Future directions
## The 1st EGRET Catalogue

### Table 7: Positive Detections on Radio-loud Quasars and BL Lac Objects

| ID     | Source ID | Characteristics | pos | Flux (10^-6 cm^-2 s^-1) | Vpe | Photon Spectral Index | z | Rel Luminosity | Ref | Other Name |
|--------|-----------|-----------------|-----|-------------------------|-----|-----------------------|---|------------------|-----|------------|
| 0202+149 | √         | √               | √   | 24 40                   | 0.26±0.06 | 21.0                | 2.5±0.1 | 1    | 4C+15.05   |
| 0208-512 | √         | √               | √   | 4 15                    | 0.4±0.12 | 9.0                 | 1.003   | 2    | PKS        |
| 0234+285 | √         | √               | √   | 22 35                   | 0.16±0.05 | 15.0                | 1.213   | 4C 28.07 | OD+258     |
| 0235+164 | √         | √               | √   | 35 28                   | 0.19±0.07 | 0.2-0.5             | 0.94    | 3    | OD+160     |
| 0420-014 | √         | √               | √   | 53 39                   | 0.19±0.07 | 0.2-0.5             | 0.92    | 1    | OA 129     |
| 0446+112 | ?         | √               | √   | 17 31                   | 0.17±0.06 | 0.2-0.5             | 1.2     | PKS        |
| 0454-463 | √         | √               | √   | 20 71                   | 0.29±0.07 | 6.0                 | 0.858   | 1    | PKS        |
| 0528+134 | √         | √               | √   | 10 11                   | 1.13±0.08 | 0.2-0.5             | 2.06    | PKS        |

*Note: Flux values are given in (E>100 MeV) and Vpe values are given in (E>100 MeV) too.*
THE RADIO DATA: LIGHT CURVES

EXAMPLE SOURCE
COMPARISON: Is This Activity Related?

Problem: limited sensitivity of EGRET & poor sampling
Statistical Evidence for Time-Correlated Activity

These correlations suggested that the same shocks produced the emissions in BOTH bands.
Gamma-ray detections do not always precede/match flares at mm/cm band: overall activity correlated but not specific flares.

Global 1995 flux increase in all of the bands shown.

The activity is broadband suggesting that the same particles are responsible for the radio emission in the jet and the $\gamma$-ray emission.

New jet pc scale components evident in mm VLBI: 04/94, 04/95
**EGRET+ SD + VLBI monitoring**

Temporal association between component ejection and flaring

VLBA monitoring data at 43, 22 GHz (Jorstad et al. 2001a,b) + epoch of flaring suggest that the $\gamma$-ray emission is produced by shocks downstream of the radio core.

From Jorstad et al. 2001b: component ejections on 1994.6, 1995.5; EGRET flares on 1994.55, 1995.51
Linear Polarization as a Marker of Shocks in the Jet Flow

The temporal association between EGRET detections, new VLBI components, & changes in LP indicate that internal shocks play a role in the generation of the gamma-ray emission.

- Arrows mark Strong EGRET detections ($F>100$).

- Detections match component ejections for 1993, 1995 events; shock signature present. (Jorstad et al. 2001)

- Increase in P%
Questions to be answered in the Fermi era

Where within the jet* is the $\gamma$-ray emission produced? (localization of physical site using light curves)

What is the emission mechanism? (character of the variability from studies of the distribution of power; SEDs)

What is the mechanism for the acceleration of particles? (tests for the presence of shocks during gamma-ray flaring)

What special conditions are present in the jet during broad band flaring? (identification of jet properties during flaring and of changes in jet conditions from flare to flare)

* Rapid variability in some sources suggests an emission site near the central engine but see Marscher and Jorstad paper this meeting.
## Current monitoring programs

| Program      | Frequency (GHz) | sampling      | Size/advantage                                      |
|--------------|-----------------|---------------|-----------------------------------------------------|
| OVRO         | 15              | 2-3/week      | >1150 many sources: low S                           |
| Effelsberg   | 2.64 - 43       | monthly       | ≈60 spectra                                         |
| IRAM         | 86 - 270        | monthly       | ≈ 60 inner jet                                      |
| UMRAO        | 4.8, 8.0, 14.5  | 1-2/week      | 35 in core group mf; includes LP                    |
| Metsähovi    | 37              | monthly       | ≈100 inner jet                                      |
| RATAN-600    | 1-22            | 2-4/year      | 600 spectra                                         |

The combined data provides both temporal and spectral coverage.
Evidence for correlated activity: **Fermi** + MOJAVE + SD

Time-averaged data for 77 MOJAVE sources in 3-month bright AGN list

Photon flux 2008: august-october

---

**Figure 1.** Average *Fermi* LAT 100 MeV–1 GeV photon flux (Abdo et al. 2009b) vs. quasi-simultaneous 15 GHz flux density. The filled circles represent total VLBI flux density while open ones—single-dish flux density. The single-dish flux densities are representative of the parsec-scale emission in these objects as described in Section 2.

Result: A high-confidence positive correlation is found using a statistically complete sample.

Kovalev et al. April 2009
Radio band – Gamma-ray Correlations

OVRO versus Fermi flux density; time-averaged data for 49 sources with known redshift in the 3 month bright AGN list

Correlation coefficient=0.56;
Chance probability=5\times10^{-4}

Figure 6: OVRO 15 GHz flux density versus Fermi-LAT 100 MeV flux density.

Richards et al. Nov 2009
# LIGHT CURVES: localization and emission process

## Source Property
- lags, leads (localization)
- Time scale, noise process
- Degree of variability
- Periodicity
- Length of data trains:
  - radio: up to 4 decades
  - gamma-ray: 2 years

## Common Method
- Cross correlations
- Structure functions
- FI, normalized excess variance
- Cross-wavelets
Result: A variety of patterns is found based on these short data trains. (Top two shown dominated by a single event; gamma leads radio)
Inherent Problems in Using Cross-Correlations of Light Curves for Localization:

- Unambiguous identification of the SAME event is difficult except when the light curve is dominated by a single event (e.g. 0235+164).
- Self-absorption and opacity produce delays.
- A `long’ data train is required to capture the full range of behavior which can change from epoch to epoch.
- Changes in the parameters regulating the emission as a function of waveband may change with time.
Inter-band TIME LAGs

EGRET result for 3C 279

Patterns change with time in the same source. (No persistent trends in general.)

RESULT: Time-dependence may reflect variations in input parameters (Böttcher and Dermer 2010).

Hartman et al. 2001
Characterization of the Emission: timescales & noise process from 1st-order structure function analysis

Turnover gives the maximum correlation time scale. Using data thru 2005, $\tau=0.87$ yrs; $\tau/(1+z)=0.45$ yrs. The value obtained can be a function of the time window.

Slope ‘measures’ noise process.

\[ D(\tau) = \langle [S(t) - S(t + \tau)]^2 \rangle = 2\sigma^2(1 - \rho(\tau)) \] for stationary noise

\{ $D \propto \tau^\alpha$ → “measures” process
\{ $\tau < \tau_c$ → measures correlation time scale

\[ \log(D) \] vs. \[ \log(\tau) \]
Character of the Variability During the First 11 months of Fermi Operation 08/04-2008 – 07/04/09

Fermi: E>300 MeV; 1 week average

Dominated by a single `event’

Fermi SF for 0235+164

Cm-band: 4.8-14.5 GHz: 1 wk average

Dominated by a single event but timescale longer
Results from Long-term UMRAO Data: quasi-periodic behavior (wavelets, cross-wavelets)

Independent analysis of 25 years of optical + radio data (Raiteri et al. 2001) gave P=5.7 +/- 0.5. Next event did not follow expected pattern.

Radio band: Different methods identify different `periods': all are yrs.
Are Similar Emission Properties Apparent?

- Slope of SF (noise process): $0235+164$ and $3C\,454.3$ dominated by a single event in BOTH bands in Fermi era. In general: radio band $b=1$ (shot noise), in gamma band $b\approx0.0$ (white noise) sometimes.

- Characteristic times scales:
  \[ \tau \approx 2 \text{ years at cm band (from SF analysis)}. \]
  \[ \tau \approx 7 \text{ weeks at gamma ray band (from DACF lag times)}. \]

- Periodicity:
  quasi periodicity in several sources $>\text{year at radio band}$. None yet at gamma ray band. OJ 287 best case in radio. don’t know yet.
Characteristic SEDs: study of the relation of SSC and IC components using quasi-simultaneous data (Aug-Oct 08)

- **1510-089**
  - LSP FSRQ
  - Compton Dom.=7.4

- **0235+164**
  - LSP BL
  - Compton Dom.=1.5

- **3C66A**
  - ISP BL
  - Compton Dom.=1

- **Mkn 501**
  - HSP BL
  - Compton Dom.=0.5

Analysis uses SD monitoring data

Abdo et al. submitted
Evolution of the SED: 3C 279 During Activity

RESULT: The Mf behavior is complex.

Abdo et al. 2010
Evolution of the SED During γ-ray Flaring

Evolution of the SED during a single `event’

**Figure 2** | Energy spectrum from radio to γ-ray band of 3C 279 at two different epochs. The red points were taken between 54880 and 54885 MJD, corresponding to the first five days of the sharp γ-ray flare accompanying the dramatic polarization change event (epoch 1). The blue points were taken between 54950 and 54960 MJD, around the peak of the isolated X-ray flare.

**RESULT:** significant changes are present in all bands except the radio.

Abdo et al. 2010
SHOCKS: A Mechanism for Particle Acceleration

August 2008 event: 1502+106

Evidence for shocks during flaring from MOJAVE VLBP measurements: 1502+106

Abdo et al. 2010
Example of Shock Signature in LP data
Description of UMRAO Oblique Shock Models (evolution of mf LP light curves)

- The models are determined essentially by two free parameters: the shock compression and the shock direction (forward or reverse). The latter is expected to be important for time delay considerations.

- An extreme relativistic equation of state is assumed.

- A shock is introduced into the relativistic flow at \( t=0 \) at an oblique angle to the flow direction.

- Both simulated light curves and images are generated for comparison with the data.
**Simulation from Radiative Transfer Calculations**

Representative Light Curves

*Specification of shock:*
*Forward moving shock*
*Compression=0.7*

Lorentz factor of flow=2.5
Lorentz factor of shock=6.7
Viewing angle=10 degrees
Primary Features of the light curves

1. Total flux outburst
2. Increase in linear polarization to near 10%
3. Swing in EVPA thru 40 degrees
4. Spectral behavior
Simulated structure images
Summary of Results Based on Combined Fermi and Single Dish Monitoring Data

♣ Flux-flux correlations obtained using time-averaged quasi-simultaneous data are highly significant. These argue for correlated broadband activity.
♣ Cross-correlations of the light curves show a variety of behavior patterns. Localization of the emitting region using these data must account for a number of factors potentially affecting the cross-correlation results.
♣ The association of rare, dramatic events in both bands can be easily identified, but in general the emission processes are different with respect to both noise process and characteristic time scale.
♣ Linear polarization monitoring verifies the presence of oblique shocks during gamma-ray flaring. In combination with modeling, the data can be used to identify jet conditions during gamma-ray flaring.
Future Work

- Deviations from the simple scenario of one mechanism/one site must be addressed:
  - rapid/hourly variability in 1510-089 (Tavecchio et al.) vs evidence for origin near core (e.g. Pushkarev)
  - differences in class properties (Leon-Tavares)

- More detailed investigation of the character of the variability must be carried out as the Fermi data accumulates; if changes occur in both the radio and gamma-ray bands this would support the view that the emissions are causally related.

- Isolation of the specific conditions giving rise to gamma-ray flaring must be identified; these include searches for changes in jet properties from event to event in the same source.