

# The Fermi/LAT multi-wavelength campaign of 3C 454.3 during the 2008-2009 outburst period

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Collaboration + many multi-wavelength collaborators\*



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für Radioastronomie

During the early phase of Fermi/LAT operations in July 2008, the quasar 3C 454.3 was detected in outburst showing highly variable gamma-ray emission for a period of about 140 days. A large LAT multi-wavelength campaign was organized during July 2008 and March 2009 providing a unique, detailed data base with nearly complete frequency coverage: radio cm/mm/sub-mm, IR, optical, Swift UV and X-ray bands including optical polarization, Spitzer near-IR and multi-frequency VLBI observations. Here, we present the analysis and results of this intensive campaign in the context of the overall activity phase of the source during 2007-2009.

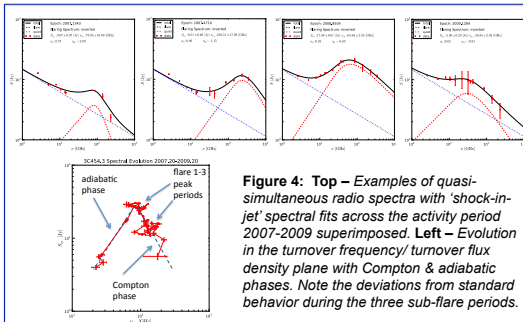
## Multi-wavelength observations

During the early phase of Fermi/LAT (July-October 2008):

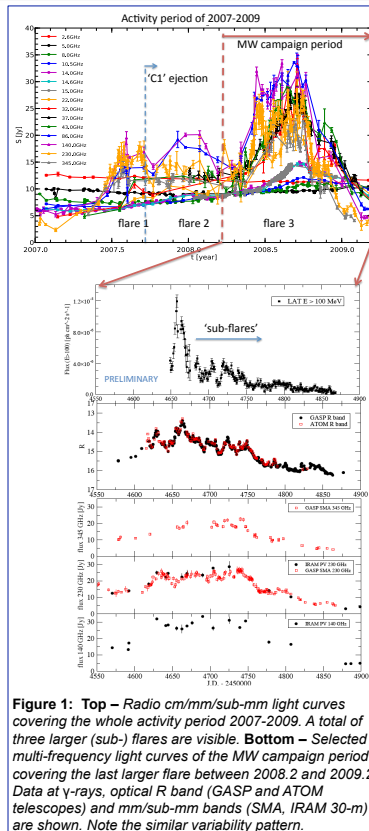
- strong and highly variable  $\gamma$ -ray emission from quasar 3C 454.3 (Abdo et al. 2009) indicating a highly compact emission region and relativistic beaming with  $\delta > 8$
- existence of a spectral break in the  $\gamma$ -ray spectrum (e.g. an intrinsic break in the energy distribution,  $\gamma$ -ray absorption or superposition of spectral components, e.g. Abdo et al. 2009, Finke & Dermer 2010)

In addition:

- large Fermi multi-wavelength (MW) campaign (Abdo et al. in prep.). Period: July 2008 to March 2009 (see Fig. 1, bottom) with unprecedented frequency coverage:
- total intensity, optical polarization and VLBI observations
- bands: cm/mm/sub-mm, IR/optical/UV, X-ray, GeV
- including: OVRO and F-GAMMA cm to mm (Effelsberg/IRAM) monitoring programs, GASP (radio/IR/optical) collaboration with many IR/optical telescopes (radio: UMRao, Metsähovi, SMA, Medicina, Noto), Kanata, ATOM, SMARTS, Stewart observatory, VLT/VISIR, Spitzer near-IR and Swift UVOT/XRT/BAT
- VLBI: 17 epochs of the Boston 43 GHz monitoring and a VLBA multi-frequency ToO program (4 epochs in Sept./Oct. 2008)



**Figure 4: Top** – Examples of quasi-simultaneous radio spectra with 'shock-in-jet' spectral fits across the activity period 2007-2009 superimposed. **Left** – Evolution in the turnover frequency/turnover flux density plane with Compton & adiabatic phases. Note the deviations from standard behavior during the three sub-flare periods.

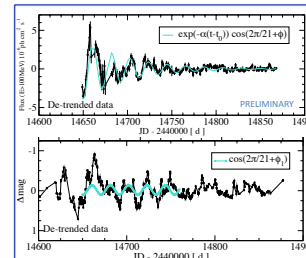


**Figure 1: Top** – Radio cm/mm/sub-mm light curves covering the whole activity period 2007-2009. A total of three larger (sub-) flares (flare 1-3) are visible. **Bottom** – Selected multi-frequency light curves of the MW campaign period covering the last larger flare between 2008.2 and 2009.2. Data at  $\gamma$ -rays, optical R band (GASP and ATOM telescopes) and mm/sub-mm bands (SMA, IRAM 30-m) are shown. Note the similar variability pattern.

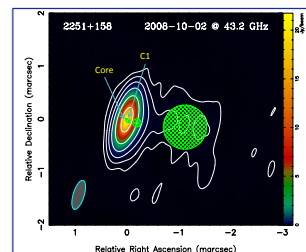
## Multi-wavelength analysis

Using the collected, large MW data set, a detailed MW analysis was performed. This covers:

- detailed time series & cross-band analysis (structure function, Lomb-Scargle periodogram, CCF)
- detailed analysis of optical polarization, the MW spectral behavior (radio cm/mm/sub-mm; IR/optical/UV; X-ray;  $\gamma$ -ray) as well as detailed shock-in-jet modeling (Marscher & Gear 1985, Türler et al. 2000, Fromm et al. submitted) at cm/mm/sub-mm bands
- model fitting of VLBI epochs and analysis of the 43 GHz VLBI jet kinematics between June 12, 2008 (JD 2454630) and September 16, 2009 (JD 2455091)



**Figure 2:** Examples of periodicity analysis showing de-trended  $\gamma$ -ray (top) and optical R band (bottom) light curves. In both cases a 21-day periodicity is found.



**Figure 3:** VLBI image of 3C 454.3 at 43 GHz during the MW campaign (October 2, 2008): a compact core-jet source is seen with core and jet model components superimposed.

## Multi-wavelength results

### Time series & cross-band analysis:

- MW light curves in Fig. 1: Fermi/LAT and MW campaign period of 2008/2009 was part of a longer activity/flare period consisting of a series of three larger (sub-) flares (flare 1-3) occurring between 2007 and 2009.
- Fermi  $\gamma$ -ray flare: during the (larger) 'flare 3' and corresponding high flux states at all bands (IR/optical/UV/X-ray including cm/mm radio bands, see Fig. 1)
- **here:** detailed sub-structure with a first larger (double-) peak and subsequent lower amplitude sub-flares (Fig. 1 bottom). Similar radio sub-structure is only visible above  $> 100$  GHz, i.e. in the optically thin regime (see Fig. 4)
- correlated  $\sim 140$  days variability period (JD 2454610-2454750) and variability cycles with a quasi-periodic modulation of 21 days at  $\gamma$ -ray, X-ray and optical R band
- at optical R band & mm-band: additional quasi-periodicity with  $\sim 63$  days, optical seems to lead by  $\sim 3$  days
- CCF and periodicity analysis: strong correlation of  $\gamma$ -ray, X-ray and optical R band with possible delays between 1-3 days (X-ray leading), cm-bands successively delayed w.r.t. 1 mm band

### Optical polarization behavior:

- no clear sign of a systematic polarization angle swing during the flaring activity
- the polarization degree varies between 0 - 10% with a maximum during the optical high-flux state

### Broad band spectral behavior:

- no strong spectral evolution at  $\gamma$ -ray, X-ray and optical R band during the campaign. Thermal components (BLR, accretion disk) appear at lower flux states

### VLBI spectra and 43 GHz jet kinematics:

- variability from VLBI core region (core & first jet component, see Fig. 3), on scales  $\sim < 0.1$  mas, i.e.  $< 0.8$  pc
- new VLBI component ejections: (i) new component 'C1' in the early phase of activity (during 'flare 1'): Sept. 26, 2007 (JD 2454370)  $\pm 46$  days with a speed of  $0.13 \pm 0.02$  mas/year =  $6.1 \pm 0.8$  c (see also Jorstad et al. 2010) and (ii) new component after the activity period: June 23, 2009 (JD 2455005)  $\pm 70$  days
- core: triple sub-structure on 43 GHz "super-resolution" and 3 mm VLBI images (Jorstad et al. 2010, Krichbaum et al.)

### Shock-in-jet modeling:

- radio spectral evolution between 2007.2 and 2009.2: overall activity period follows standard shock-in-jet scenario (see Fig. 4) with a Compton & adiabatic phase, supported by increasing time lags towards cm-bands
- during the 'flare 1-3' peak phases: superimposed deviations from standard model

\* This work is done together with many MW collaborators, not mentioned all here due to limited space. Here, we thank in particular K. Sokolovsky, C. Fromm, N. Marchili (MPIfR), L. Escande, B. Lott (CENBG), S. Cutini (ASDC) and K. Nalewajko (CAMK)

## Summary & conclusions

3C 454.3 showed a very complex MW behavior during the activity period of 2007-2009. Some main features are:

### MW campaign period ('flare 3'):

- quasi-periodic modulations together with the absence of strong broad band spectral changes favor variability due to motion in a helical jet with  $\sim 100$  Schwarzschild radii diameter ( $M_{\text{BH}}=10^9 M_{\text{Sgr}}$ ) and  $\delta \sim 10$ . A similar behavior was seen in 2005 (see Krichbaum et al. 2010)
- broad band ( $\gamma$ -ray to mm) variability produced in the inner core region: on sub-pc scales

### Overall activity period ('flare 1-3'):

- probably only one component ('C1') related to overall activity
- shock-in-jet modeling and VLBI timing/evolution: (i) propagation of an evolving shock (most likely component 'C1') responsible for the overall variability (ii) a 'shock/standing shock' interaction scenario (e.g. the shock moving through the core triple sub-structure) could be invoked (see also Jorstad et al. 2010) to explain departures from the standard model (Fig. 4) and produce the overall triple flare structure ('flare 1-3' in Fig. 1)

### References:

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