Blazar physics
through multi-frequency circular and linear polarization monitoring

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Linear and Circular polarimetry

powerful tool but challenging endeavor

Investigate
- physical conditions
- emission processes
- variability mechanisms

Challenging due to
- low levels of LP and especially CP
- high levels of variability
- instruments specialize on either LP or CP

Design and development of an **end-to-end framework**
- novel LP and CP data reduction pipeline
- full-Stokes radiative transfer model of astrophysical plasma systems (e.g. AGN jets)

\[ I_{\text{peak}} = 749 \text{ mJy} \]
\[ \text{LP}_{\text{peak}} = 25 \text{ mJy} \]
\[ \text{EVPA} = -6^\circ \]
\[ dT = 18 \text{ days} \]

\[ I_{\text{peak}} = 860 \text{ mJy} \]
\[ \text{LP}_{\text{peak}} = 13 \text{ mJy} \]
\[ \text{EVPA} = -68^\circ \]

credit: VLBA-BU Blazar Monitoring Program
F-GAMMA program (Jan 2007 — Jan 2015):
- almost 90 mostly Fermi sources
- mean cadence ~ 1.3 months
- 2.64–345 GHz at 11 frequency steps
- 8yr data release soon

see also poster:
“F-GAMMA: monthly light curves of Fermi blazars”

+ follow-up monitoring with Effelsberg
- 2.64–43 GHz at 8 frequency steps
- mean cadence ~ 10 days

Fuhrmann et al. 2016A&A...596A..45F
Angelakis et al. 2010, astro-ph.CO/1006.5610
Fig. 17. Flux density and three-point spectral index curves. In each plot the upper panel shows the flux density at all \( F \)-GAMMA frequencies, while the lower one shows the low and intermediate-frequencies spectral indices as functions of time (the spectral index \( \alpha \) is defined as \( S \propto \nu^\alpha \)). Each frequency is marked always by the same color. The plots are marked with the \( F \)-GAMMA source name and the survey name whenever available.
F-GAMMA

science highlights

- γ-ray loudness and radio variability
- γ-ray emission site
- radio vs γ-ray fluxes (S-S correlations)

Fuhrmann et al. 2016A&A...596A..45F
SED variability patterns can be reproduced by the combination of:

- a power-law quiescent spectrum with $S \sim \nu^\alpha$ attributed to the optically thin emission of a large scale jet
- a convex synchrotron self-absorbed spectrum caused by recent outbursting superimposed on the quiescent part.

Angelakis et al. in preparation
New LP and CP data reduction pipeline
high-precision radio polarimetry

Complete pipeline
- from telescope observables to $I, Q, U, V$

Several correction steps
- pointing, opacity, elevation-dependent gain

Careful treatment of telescope response
- Airy disk instead of gaussian beam pattern

Minimization of instrumental effects:
- instrumental LP correction across the telescope beam
- absolute EVPA calibration with Lunar observations
- instrumental CP correction with two independent methods

Designed for CP feeds but easily applicable also to LP feeds

see also poster: “Linear and circular polarization standard sources in the GHz regime”

Myserlis et al., Galaxies, vol. 4, issue 4, p. 58
Linear and circular polarimetry with Effelsberg
new, high-precision data analysis methodology

Uncertainties:
- LP degree: 0.1 %
- CP degree: 0.1—0.2 %
- EVPA: 1°

High-cadence, full-Stokes light curves
- LP at 2.64, 4.85, 8.35, 10.45 and 14.6 GHz
- CP at 2.64, 4.85, 8.35, 10.45, 14.6, 23.05 GHz
- mean cadence: ~ 1 month
- time baseline: 2010.5 - now

Sources with stable polarization over 5.5 yrs
July 2010 – April 2016

$\langle \sigma \rangle = 0.1\%$

$\langle \sigma \rangle = 1.7^\circ$

$\langle \sigma \rangle = 0.1\%$

Static results / Population studies using median values

- **B-field strength**: \( \sim 5 \text{ mG} \)
- **plasma composition**: \( \sim 1:2 \) (e\(^-\) vs e\(^+\))
- **Faraday rotation levels consistent with galactic low-energy plasma content**
- **poloidal** B-field component dominance

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![Histogram of the alignment between the EVPA at 0\(\lambda\)-wavelength (\(\chi_0\)) and jet PA (\(\phi_{jet}\)).](image)

**3C 111**

0415+379: stack of B2 MOJAVE/2cm Nat.Wgt.Epoch:
Bm:0.89x0.57 mas at -7\(^\circ\);
Cntrs: \(\sqrt{2} \times 0.2\) mJy/bm

**MOJAVE program**
**Lister et al. (2009)**
Dynamic results / Time domain studies using multi-frequency, LP and CP variability

- full-Stokes radiative transfer model of astrophysical plasma systems
- AGN jet modeling with turbulent B-field configuration
- variability induced by shocks propagating downstream
- tested in both low and high $\gamma_{\text{min}}$ regimes
**the high-$\gamma_{\text{min}}$ regime:**

Shock parameters

- Compression factor: $k = 0.8$

- $\gamma_{\text{min}} \sim 10^4$

- Doppler factor: $D \sim 30$
  Consistent with $D_{\text{var}}$ at 37 GHz
  Hovatta et al. (2009)

Jet plasma parameters

- Density: $n_0 = 10^1 - 10^2 \text{ cm}^{-3}$

- Magnetic field coherence length: 9 pc

*Myserlis, Angelakis et al., in prep.*
*Myserlis et al., Galaxies, vol. 4, issue 4, p. 58*
the low-$\gamma_{\text{min}}$ regime: NGC 4845

Irwin et al, 2015, ApJ...809..172I

- SSA spectrum with $v_{\text{max}} \sim 1.8$ GHz ✔
- LP practically zero (0.1–0.5 %) ✘
- CP
  - extremely high at 1.5 GHz: 2–3 % ✔
  - zero at 6 GHz ✔

Realisation
- conical adiabatically expanding outflow
- random B-field

We find:
- Faraday effects play a key role
  - decrease LP at 1 GHz
  - increase CP 1 GHz

Low LP at 6 GHz cannot be reproduced with this realisation
- excess of thermal plasma in within or around the outflow
Summary

LP and CP are powerful tools to study blazar physics: physical conditions, emission processes and variability mechanisms

Broadband radio data (F-GAMMA + beyond): spectral variability due to evolving SSA components
- track expected coordinated LP and CP changes
- constrain physical conditions

Developed an end-to-end framework for LP and CP studies
- high precision polarimetry
- recovered LP and CP data for four frequencies (2.64, 4.85, 8.35 and 10.45 GHz):
  - LP and CP light curves and spectra
  - spin-off result: LP and CP calibrators

Static results / population studies
- B-field: ~ 5 mG
- plasma composition: ~ 1:2 (e⁻ vs e⁺)
- faraday rotation due to galactic low-energy plasma
- poloidal B-field component dominance (with FSRQ and BLLac dichotomy)

Dynamic results / time domain studies
- full-Stokes radiative transfer model of astrophysical plasma systems
- AGN jet modeling with turbulent B-field configuration and variability by propagating shocks
- successfully tested in both low and high γmin regimes
- constraints for Doppler factor, compression factor, plasma density and B-field coherence length