Using mm-VLBI and single-dish methods to localize the high-energy emission from the blazar PKS 1502+106

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Motivation

Blazars are among the most variable and most broadband emitters of radiation in the Universe. The detailed processes that give rise to those characteristics though, remain still unclear. Combining VLBI and single-dish data we are able to shed light on the compact regions where most of the blazar activity takes place. The blazar PKS 1502+106 at z=1.834 is a promising example, having exhibited extreme and correlated, radio and high-energy activity that triggered intense single-dish and GMVA monitoring down to 3 mm, enabling the sharpest view to date towards this extreme object. Our data set comprises 6 epochs at 43 and 86 GHz along with 19 reanalyzed observations at 15 GHz (MOJAVE). The single dish data were obtained within the F-GAMMA blazar monitoring program. The data follow the flare that started in 2008 and continued for almost 5 years, with high cadence.

The 3mm VLBI core

Jet kinematics

A linear fit to the radial separation of components yields the apparent speeds of different components within the flow. The most extreme superluminal motion of about 22 c (at 15 GHz) constrains the critical viewing angle towards the source to 2.6°.

Apparent & intrinsic opening angle

We obtain the apparent opening angle of the jet by fitting the de-convolved effective size of the resolved components at all 3 frequencies (15, 43 and 86 GHz). The resulting opening angles θ_{int} are between 1.6° and 2.2°.

Distance of 3 mm VLBI to the cone vertex

Under the assumption that the core takes up the entire jet cross section, the de-projected distance of the 3 mm core from the vertex of the hypothesized conical jet can be estimated by

$$d_{core} = 1.8 < FWHM >_{core}/2 \; \tan(\theta_{int}/2)$$

It is found to be ≤12–16.5 pc. A discussion of a few important considerations can be found in Clausen-Brown+ (2013). For a sketch of the jet of PKS 1502+106 see Fig. 2.

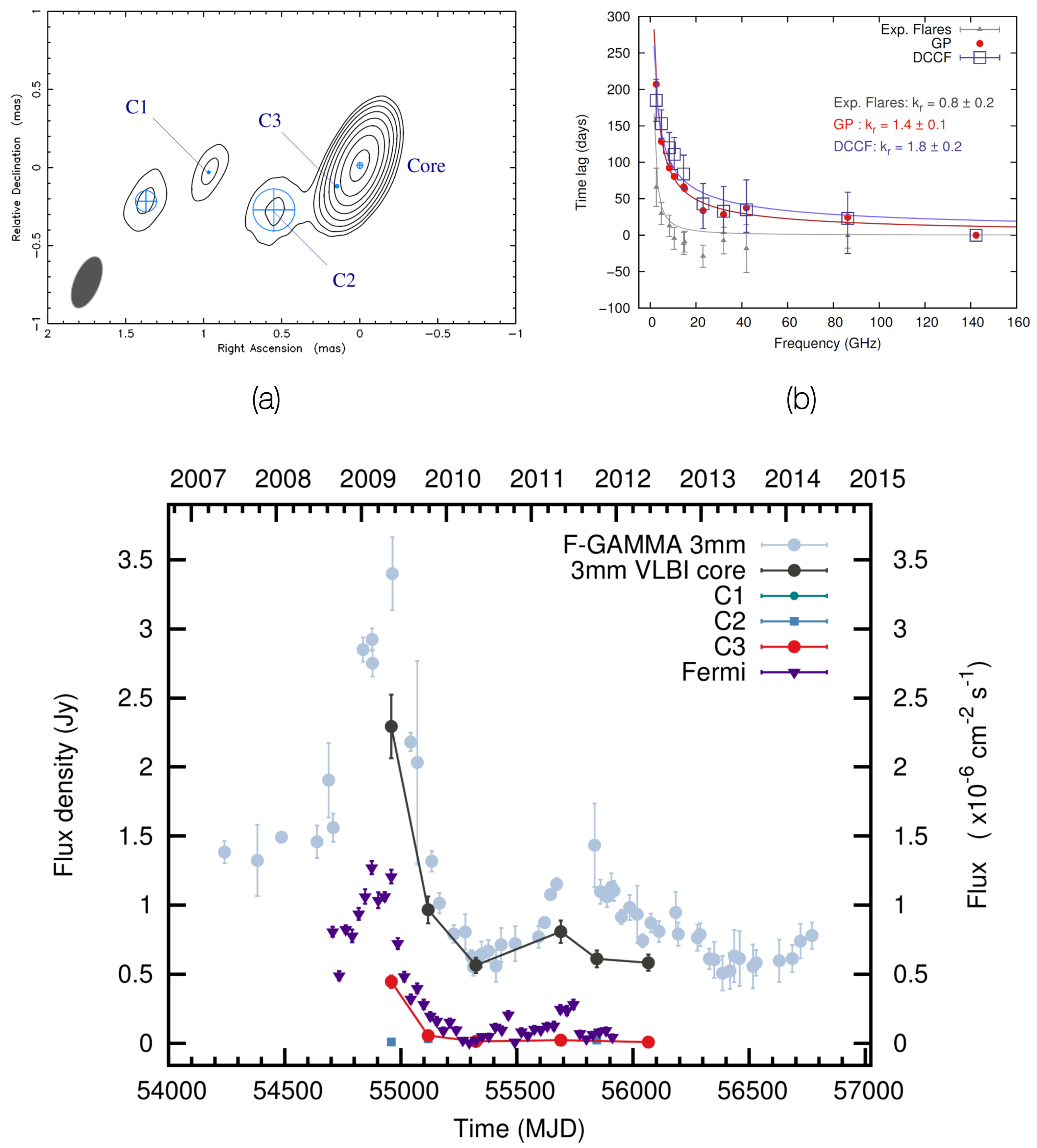

Fig.1 (a) 3 mm VLBI modelfit map of PKS 1502+106 at epoch 2010.34. Contour levels at 0.1% up to 19.2% of the peak flux density of 2.23 Jy/beam; (b) Time lags at all radio frequencies wrt 2 mm F-GAMMA data revealing the opacity structure of the source; (c) Single-dish, total intensity light curve (LC) at 3 mm along with individual VLBI component LCs at the same frequency. The *Fermi*/LAT gamma-ray LC is shown additionally, highlighting the correlated activity at different bands.

Single-dish analysis

Opacity structure of the source

Our F-GAMMA (Fuhrmann+ 2007, Angelakis+ 2010) broad band, multi-wavelength data span 11 frequencies (11 cm to 1 mm) and ~7 years in time. In Fig. 1 (c) the 3 mm F-GAMMA light curve (LC) is shown, along with LCs of VLBI components and the core; also visible is the *Fermi*/LAT LC. For the extraction of the relevant LC parameters we perform a fit with three methods. An exponential decomposition, a non-parametric Gaussian process (GP) approach, and a DCCF analysis are employed. Each LC is fitted separately. The flare amplitude, time scale and time of maximum flux density, S_{max}, are extracted next. Based on the different time of S_{max} we gain insights into the opacity structure of the jet of PKS 1502+106. The method provides an alternative to VLBI core-shift measurements (e.g. Kudryavtseva+ 2011, Kutkin+ 2014). The results of the time lag analysis wrt the 2 mm data are presented in Fig.1(b). The average 23.9-day time lag between the 3 and 2 mm peak flux densities translates into a distance of the core from the vertex of the cone of ~4.1 pc.

Cross correlation analysis

Analysis using the cross correlation function between the 3 mm and the gamma-ray light curves reveals that radio emission lags behind the high-energy one by 14 ± 11 days with a statistical significance above 99% (Fuhrmann+ 2014). This lag translates into a 2.1 pc de-projected distance upstream of the 3 mm core.

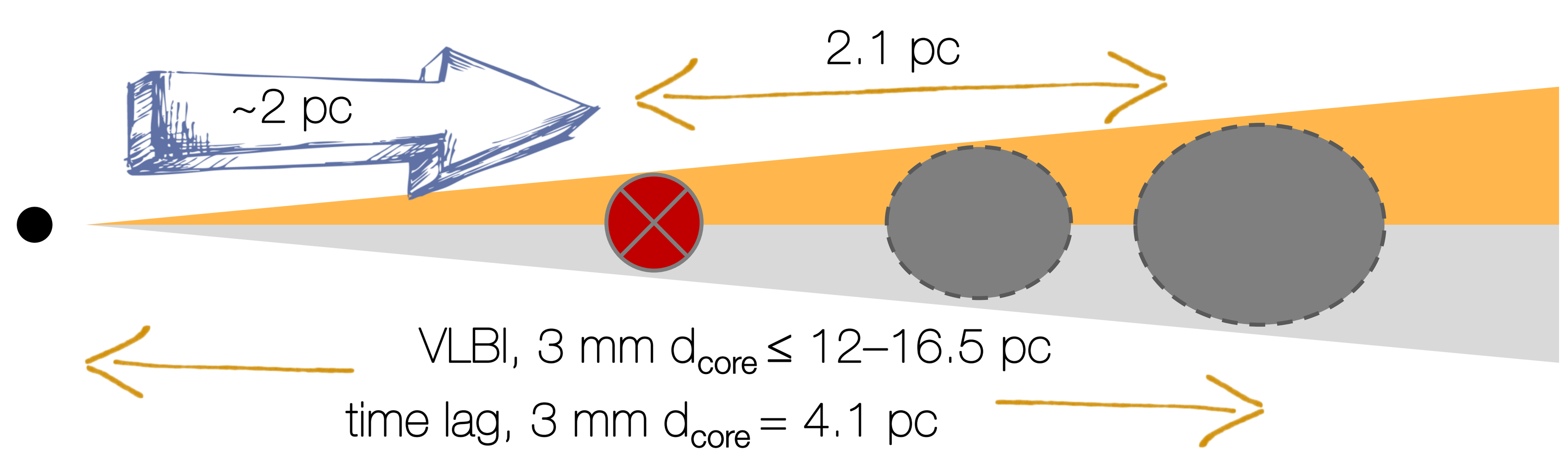

Fig.2: A sketch of PKS 1502+106 incorporating the observed features.

References | Angelakis, E. et al. (2010) arXiv:1006.5610 - Clausen-Brown E. et al. (2013) arXiv:1301.5751 - Fuhrmann, L. et al. (2007) AIP, 921,249 - Fuhrmann, L. et al. (2014) MNRAS, 441, 1899 - Kudryavtseva, N. A. et al. (2011) MNRAS, 415,1631 - Kutkin, A. M. et al . (2014) MNRAS, 437, 3396

Conclusions and outlook

- PKS 1502+106 exhibits extreme and significantly correlated activity in radio and gamma rays.
- Using VLBI images at 3 mm, single dish radio time lags and radio to gamma cross correlation we are able to pinpoint the gamma-ray emission region. Our results indicate that It is located at ~2 pc away from the vertex of the hypothesized conical jet, setting the aforementioned figures as lower limits for the distance between the black hole and the gamma-ray production region.