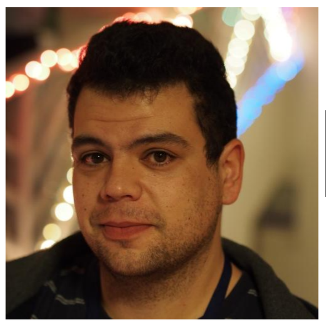

F-GAMMA: Multi-wavelength variability Doppler factors

I. Liodakis[1,2], N. Marchili[4], E. Angelakis[3], L. Fuhrmann[3], I. Nestoras[3], I. Myserlis[3], V. Karamanavis[3], T. P. Krichbaum[3], A. Sievers[5], H. Ungerechts[5], J. A. Zensus[3]

[1]Department of Physics and ITCP {Institute for Theoretical and Computational Physics, formerly Institute for Plasma Physics, University of Crete, 71003, Heraklion, Greece,
[2]Foundation for Research and Technology - Hellas, IESL, Voutes, 7110 Heraklion, Greece,
[3]Max-Planck-Institut fur Radioastronomie, Auf dem Hugel 69, 53121 Bonn, Germany,
[4]IAPS-INAF, Via Fosso del Cavaliere 100, 00133, Roma, Italy,
[5]Instituto de Radio Astronomia Milimetrica, Avenida Divina Pastora 7, Local 20, 18012 Granada, Spain.

Abstract

Understanding the relativistic effects holds the key to uncovering the true nature of blazars and their jets. To that end, several methods have been proposed in order to estimate the Doppler factor. Using population models we were recently able to show that the variability Doppler factors using the equipartition brightness temperature (5x10^{10}K) is the only method that can adequately describe both the BL Lac object (BL Lacs) and Flat Spectrum Radio Quasar (FSRQ) populations with on average 30% error on each estimate. We built on this method by using sophisticated and specially designed algorithms and multiwavelength radio light curves (from 2.64 to 142.33 GHz) in order to estimate the Doppler factor for 58 sources of the F-GAMMA program. Our novel and innovative approach allows us to effectively constrain the variability brightness temperature and produce the most accurate Doppler factor estimates yet with 16% error on average.

We estimate the Doppler factor in each source using the upgraded version of the algorithm introduced in Angelakis et al (2015) and the F-GAMMA multi-wavelength radio light curves to identify, model, track and characterize flares seen in multiple frequencies. Our approach consists of four different steps:

(1) Flare Modeling: For each source, a flare model is created at every available frequency. The algorithm identifies all the flares in a light curve, scales them according to their peak flux-density, and superimposes the scaled flares on top of each other to find, through a fitting procedure, a basic shape to be utilized as model (see Fig. 1).

(2) Correlation: Given *n* available frequencies for each source, an *n x n* matrix is filled with the results of cross-correlations among any possible pair of light curves, allowing for the estimation of the average delays between variations at different frequencies. This step is essential for the following algorithm which is used to locate the same flare at different frequencies.

(3) Flare Characterization: Using information from the previous steps (**Flare Modeling, Correlation**) an algorithm identifies and characterizes the flares that are visible in multiple frequencies. This way only significant events are taken into account. From the characterization we can calculate the variability timescale and flare amplitude and hence the variability brightness temperature for each flare at each frequency. The highest variability brightness temperature observed in a source provides the highest constrain to the variability Doppler factor.

(4) Error Analysis: We use the model from the first step (**Flare Modeling**) as a prior and repeat the previous step multiple times. Each time we let the model vary both in timescale and in peak flux density and examine the standard deviation of the residual of the light curve after the characterization. The extrema of the timescale and flux density parameter spaces set our uncertainty and what we quote as the error of our estimates (Fig. 2).

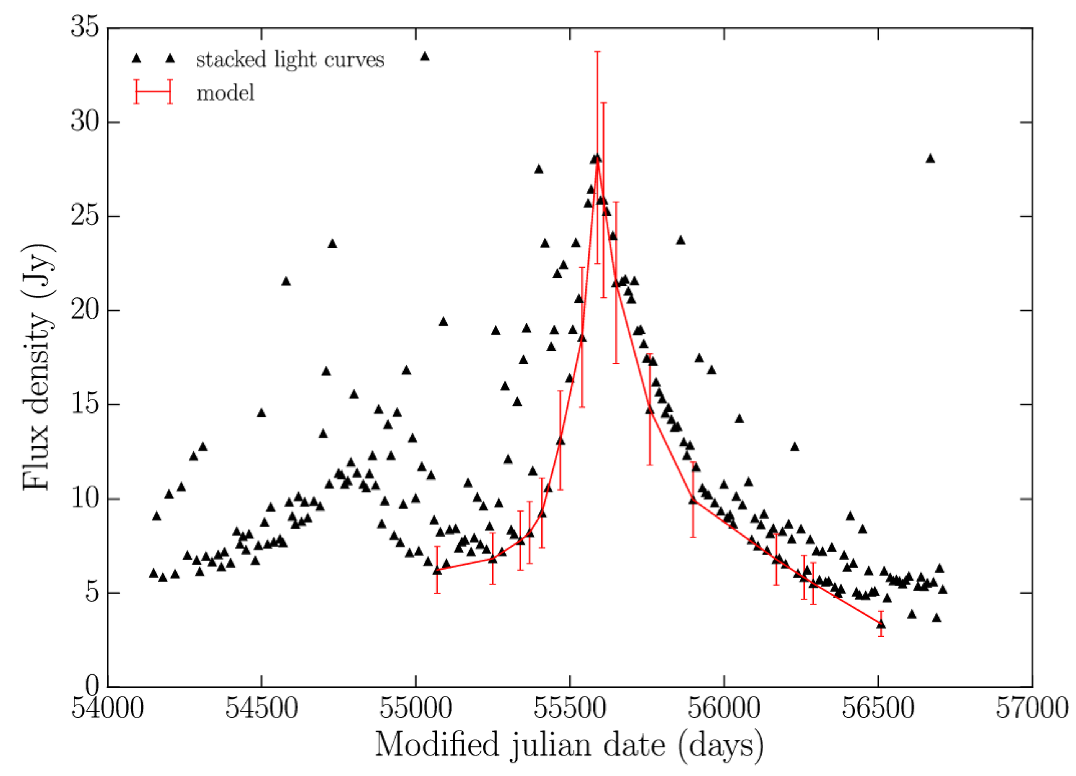

Figure 1. ***Screenshot from the flare modeling procedure for the 15 GHz light curve for 3C454.3. The black triangles are the data points of all the stacked light curves while the red line represents the basic model for the flares.***

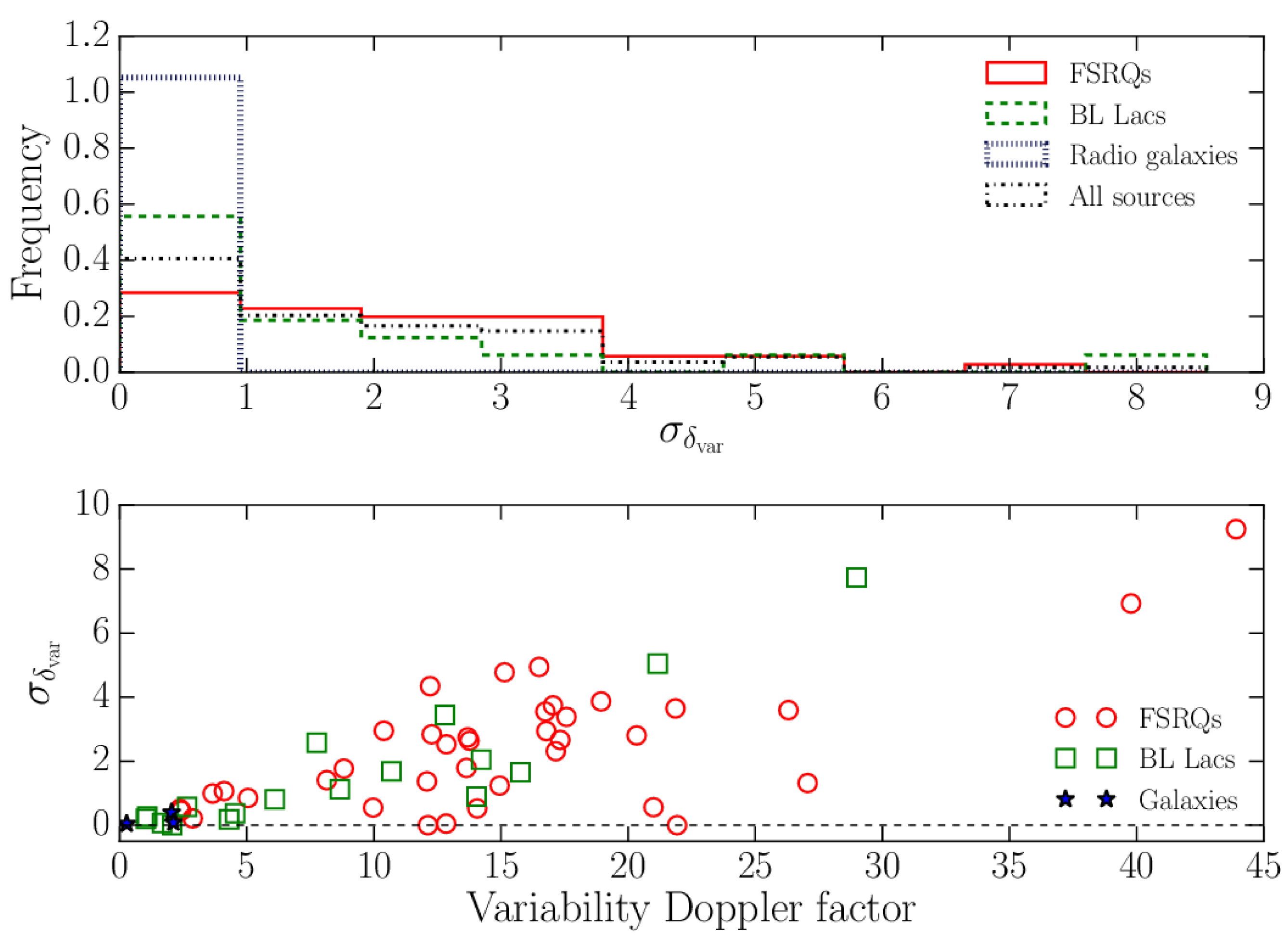

Figure 2. ***Upper panel:*** *Distribution of the error estimates of the variability Doppler factor for the F-GAMMA sources.* ***Lower panel:*** *Variability Doppler factor versus the error of each estimate.*

The highest percentage error is 35.5%, which is comparable with the on average error of the best estimates in the literature (Hovatta et al. 2009). Our on average error is **16%**. We compare our estimates to Hovatta et al (2009) which has been shown to adequately describe the blazar populations (Fig. 3).

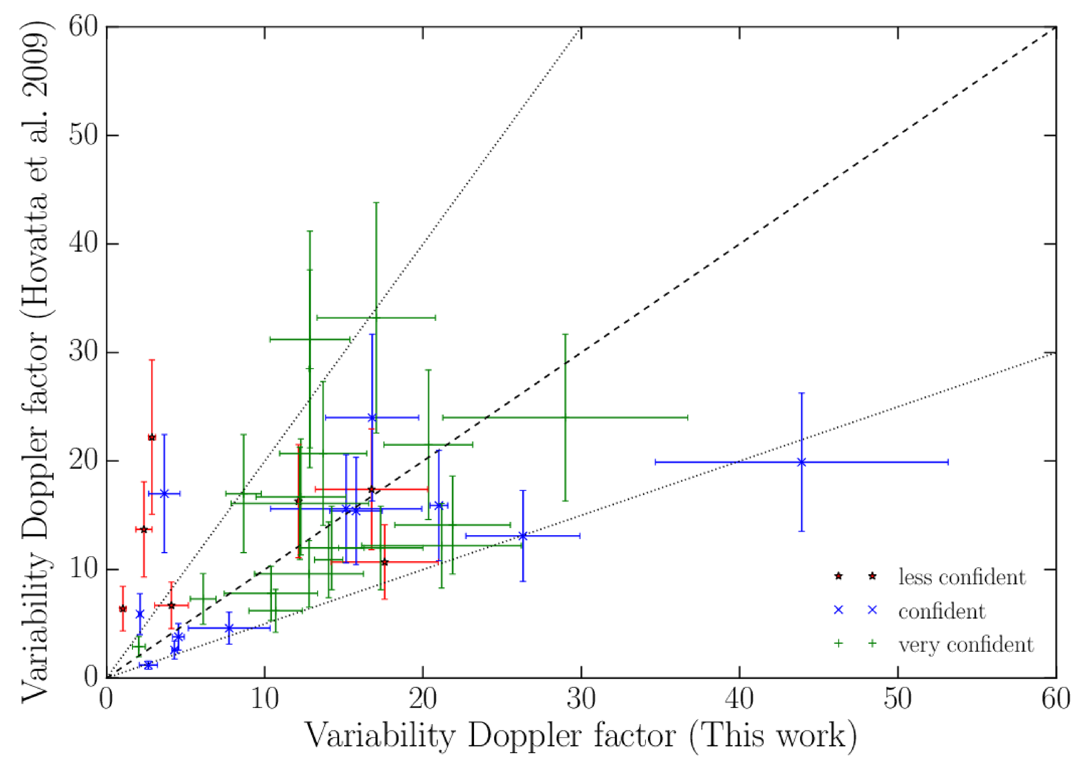

Figure 3. ***Variability Doppler factors (this work) versus the variability Doppler factors from Hovatta et al (2009). The dashed line denotes the y=x line, whereas the dotted lines mark the factor of two envelope. Red "star" is for the estimates we are less confident in our analysis, blue "x" is for the estimates we are confident, and green "+" for the ones we are very confident.***

The confidence in the estimate of the Doppler factor depends on the abundance of data points available for each source. Sparse data, large observational gaps or fewer available frequencies could severely hamper tracking the evolution and characterization of the flares which is the basis of our methodology. The two samples are found to be consistent using both the Kolmogorov-Smirnov (K-S) test (69.25% probability the two sample are drawn from the same population) and the Spearman rank order correlation test (r=0.5 with 0.1% probability of uncorrelated samples). If the sources for which we are not confident in our analysis are not taken into account in the tests, the consistency of the two samples increases (K-S test 94.4%, Spearman r=0.57, 0.08%).

Summary:

We used a novel approach and multi-wavelength radio data to estimate the variability Doppler factors for 58 of the F-GAMMA sources adding 20 new estimates in the literature. Our estimates can not only describe both blazar populations, but are also the most accurate to date with 16% error on average.

Contact Info: *liodakis@physics.uoc.gr*