The OVRO blazar monitoring program

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Abstract. The OVRO 40 m Telescope monitoring program carries out twice-weekly measurements of the 15 GHz flux density of nearly 1600 blazars and other AGN, including all those associated with northern (declination \(\geq -20^\circ\)) Fermi Large Area Telescope (LAT) detections and a preselected sample ideal for statistical studies. We present some results from the program and describe the statistical method we have developed to assess the intrinsic radio variability of the sources in our sample. We also present a method for assessing the significance of correlations between radio and gamma-ray light curves.

1. Introduction

The launch of the Fermi Gamma-ray Space Telescope in June 2008 provides an unprecedented opportunity for the systematic study of blazar jets [1]. Its Large Area Telescope (LAT) observes the sky at energies between 100 MeV and a few hundred GeV. In this energy range relativistic particles can be probed through their inverse Compton emission in the case of electron/positron jets [2, 3, 4], or a combination of pionic emission from primaries and inverse Compton emission from cascade-produced leptonic secondaries in the case of hadronic jets [5].

Blazars comprise the most numerous class of extragalactic GeV sources associated with lower-energy counterparts: the first-year Fermi point source catalog (1FGL) contains 1451 sources, of which 596 have been associated with blazars in the first AGN catalog (1LAC) [6, 7]. The exact location of the gamma-ray emission region in blazars and its proximity to the central black hole remain subjects of debate. Two possible models of the GeV emission region are that this emission comes from a “gamma-sphere” close to the base of the jet [4], or that it comes from the same shocked regions that are responsible for the radio emission seen in VLBI observations much further out in the jet [8].

The blazar monitoring program we discuss here is focused on the regular monitoring of a preselected, statistically complete sample of likely gamma-ray-bright objects, independent of their gamma-ray activity state. In anticipation of the unique opportunities offered by the Fermi-LAT sky monitoring at gamma-ray energies, three years ago we began the bi-weekly monitoring of a large sample including 1158 likely gamma-ray loud blazars, preselected according to uniform criteria, with the Owens Valley Radio Observatory (OVRO) 40-m telescope at 15 GHz.

The core sample for our monitoring program consists of the 1158 CGRaBS [9] sources north of declination \(-20^\circ\). However, we have since added (and we continue to add) to our monitoring...
program all new Fermi-LAT blazars north of $-20^\circ$ declination that are not CGRaBS members. As published, our subset of the CGRaBS sample contains 812 FSRQs, 111 BL Lacs, 53 radio galaxies, and 182 objects without spectroscopic identification. In our analysis we use redshifts from the CGRaBS publication, which covered 81% of the sample (100% of FSRQs, 49% of BL Lacs).

Our sample is statistically well defined and large enough to allow for statistical analyses and comparisons of sub-samples. We achieve a radio lightcurve sampling cadence comparable to those typically achieved by Fermi-LAT for bright gamma-ray blazars. The combination of sample size and cadence is unprecedented, making this by far the largest monitoring survey of radio sources that has been undertaken to date. Such a systematic study of radio and radio/gamma-ray population properties allows us to address a series of long-standing questions on the physical properties of blazar jets, including the location, structure, and radiative properties of the gamma-ray emission region, and the collimation, composition, particle acceleration, and emission mechanisms in blazar jets.

We discuss here the details of the monitoring program and an analysis of the radio variability of blazars [10, 11]. We also present a method for analyzing the significance of cross-correlations between radio and gamma-ray light curves [12].

2. Blazar monitoring program

Our average effective cadence for CGRaBS sources is about 128 measurements per source in the first two years of the program. The efficiency compared to our nominal cadence is 62%.

2.1. Light curves

A typical light curve for the CGRaBS program sources is shown in Figure 1. Regular updates to the data set, including data for sources outside the core sample, are available from the program website.\footnote{http://www.astro.caltech.edu/ovroblazars}

2.2. Source variability

The questions of the variability amplitude of a source and the confidence with which this can be measured are complex ones and have been traditionally addressed using a variety of measures and tests, such as structure function analysis [13, 14]; the variability index [15]; the fluctuation

\begin{figure}
\centering
\includegraphics[width=\textwidth]{light_curve.png}
\caption{15 GHz light curve for 3C454.3. Light curves for all the sources in our sample can be found in the program paper [10] and are available for download from the program website.}
\end{figure}
We propose a new index for characterizing source variability: the intrinsic modulation index $\bar{m}$, which is the intrinsic standard deviation of the distribution of source flux densities in time, $\sigma_0$, measured in units of the intrinsic source mean flux density, $S_0$. Here the term “intrinsic” is used to denote flux densities and variations as would be observed with perfectly uniform sampling of adequate cadence and zero observational error:

$$\bar{m} = \frac{\sigma_0}{S_0}.$$  \hspace{1cm} (1)

In this way, $\bar{m}$ is a measure of the true amplitude of variations in the source, rather than a convolution of true variability, observational uncertainties, and effects of finite sampling. Observational uncertainties and finite sampling will, of course, affect the accuracy with which $\bar{m}$ can be measured. We have developed a likelihood analysis, described in detail in [10], which estimates the intrinsic modulation index $\bar{m}$ and intrinsic mean flux density $S_0$, along with strictly defined 1, 2 and 3σ uncertainties.

2.2.1. Variability analysis—Results In Figure 2(a) we plot the intrinsic modulation index $\bar{m}$ and associated 1-σ uncertainty against the intrinsic, maximum-likelihood average flux density, $S_0$, for all our CGRaBS and calibrator sources. The error bar on $S_0$ corresponds to the 1-σ uncertainty in mean flux density, calculated from the joint likelihood marginalized over $\bar{m}$. CGRaBS sources are shown as black or magenta points or blue triangles for upper limits, while calibrators are shown as green points.

2.2.2. Variability analysis—Population studies—Results We now address the question of whether the intrinsic variability amplitude at 15 GHz, as quantified by $\bar{m}$, correlates with the physical properties of the sources in our sample. To this end, we will determine the distribution of intrinsic variability indices $\bar{m}$ for various subsets of our monitoring sample, and we will examine whether the various subsets are consistent with being drawn from the same distribution.

We again use a likelihood analysis and assume that the distribution of $\bar{m}$ in any subset is an exponential distribution of the form:

$$f(m)dm = \frac{1}{m_0} \exp\left[\frac{-m}{m_0}\right] dm$$ \hspace{1cm} (2)

with mean $m_0$ and variance $m_0^2$. Since distributions of this family are uniquely described by the value of the mean, $m_0$, we determine $m_0$, or rather the probability distribution of possible $m_0$ values, in any specific subset.

Figure 2(b) shows the probability density of $m_0$ for two populations. The set of sources that are included in 1LAC is depicted by a solid line, while the set of sources that are not in 1LAC is depicted by a dashed line. The two are not consistent with each other at a confidence level of 6σ, with a maximum-likelihood difference of 5.7 percentage points, with gamma-ray-loud blazars exhibiting, on average, a higher variability amplitude by almost a factor of 2 versus non gamma-ray-loud blazars. This agrees with earlier work which found that EGRET-detected AGN are more variable at radio wavelengths than gamma-ray-quiet blazars [20].

We analyze the subsets of CGRaBS BL Lacs and FSRQs. The probability densities for the mean $m_0$ of the two subsets are shown in Figure 3(a). The results for BL Lacs (FSRQs) are plotted as a solid (dashed) line. The two curves are not consistent with each other—the BL Lacs
Figure 2. (a) Intrinsic modulation index \( m \) and associated 1-\( \sigma \) uncertainty, plotted against intrinsic maximum-likelihood average flux density, \( S_0 \). Black points: CGRaBS sources found to be variable with 3-\( \sigma \) confidence by \( \chi^2 \) test; magenta points: CGRaBS sources found consistent with non-variable by \( \chi^2 \) test; green points: calibrators 3C 286, DR 21, and 3C 274; blue triangles: 3-\( \sigma \) upper limits for CGRaBS sources for which variability could not be established at \( \geq 3\sigma \) confidence level. The error bar on \( S_0 \) corresponds to the 1-\( \sigma \) uncertainty in mean flux density, calculated from the joint likelihood marginalized over \( m \). Data, except for upper limits, outside the yellow and cyan shaded areas are used in the population studies. (b) Probability density of \( m_0 \) for CGRaBS blazars in our monitoring sample that are (solid line, maximum-likelihood value and 1-\( \sigma \) error \( m_0 = 0.127^{+0.010}_{-0.009} \)) and are not (dashed line, maximum-likelihood value and 1-\( \sigma \) error \( m_0 = 0.070 \pm 0.003 \)) included in 1LAC. The two distributions are not consistent with a single value.

appear to have, on average, higher variability amplitude than the FSRQs. A similar result was found using the much longer time series data of the Metsähovi and University of Michigan Radio Observatory data sets by [21], though their result was biased by including only the BL Lacs with distinct variability features in their study.

Finally, we examine the dependence of variability amplitude on redshift. In Figure 3(b) we plot the mean \( \overline{m} \) (as calculated by a simple average rather than the likelihood analysis) in redshift bins of \( \Delta z = 0.5 \) for bright \( (S \geq 0.4 \text{ Jy}) \) FSRQs with known redshifts in our monitoring sample. We exclude BL Lacs from this analysis so as not to bias the result, as BL Lacs with known redshifts are located at low \( z \), and we have also already shown that they have a higher mean \( \overline{m} \) compared to FSRQs. Although the errors are large, there is a hint that variability amplitude decreases with increasing redshift.

3. Radio/gamma-ray time lags
The existence of correlated variability can be investigated using the cross-correlation between the radio and gamma-ray light curves. This has been done using the method of Edelson and Krolik [22], which is applicable to unevenly sampled time series and also provides error estimates on the cross-correlation for each time lag. Blazar or AGN light curves can be modelled as red-noise processes that frequently show flare-like features. These flare-like features can produce spurious
cross-correlations in unrelated time series. The distribution of these chance associations needs to be investigated in order to attach statistical significance to the cross-correlation results. An example of our data is shown in Figure 4(a).

![Figure 3](image1.png)  ![Figure 4](image2.png)

**Figure 3.** (a) Probability density of m_0 for BL Lac (solid line, maximum-likelihood value and 1-σ error m_0 = 0.112^{+0.013}_{-0.011}) and FSRQ (dashed line, maximum-likelihood value and 1-σ error m_0 = 0.080 ± 0.003) CGRaBS blazars in our monitoring sample. The two distributions are not consistent with a single value. (b) Mean m in redshift bins of 0.5 for bright (S > 0.5 Jy) FSRQs in our monitoring sample.

**Figure 4.** (a) Example radio (top panel) and gamma-ray (bottom panel) light curves. (b) Discrete cross-correlation function and its 1-, 2-, and 3-σ significance curves for the data in (a).

Due to the complexities of the sampling pattern and autocorrelation on the light curves, among others issues, the only practical way to measure the significance is through Monte Carlo simulations. A method to deal with these has been described in [23] and references therein, and will be discussed in detail in [12]. We assume the light curves can be modeled as red-noise processes with simple power-law power spectral density (S(f) ∝ f^{-β}), in which the exponent β can in principle depend on the frequency band and source. A large number of light curve pairs are simulated following a particular model. The simulated light curves are sampled as the data
are, and each data point is randomized according to the measurement error on the data. The resulting light curves are cross-correlated in the same way as the original data. Using the results for a large number of simulated light curve pairs the distribution of chance cross-correlations can be estimated at each time lag and used to estimate the probability of a chance cross-correlation. The results depend on the chosen power-law exponent and the particulars of the sampling. For the power-law exponent we use $\beta \sim 2 - 2.5$ for radio and $\beta \sim 1.5 - 2.0$ for gamma-rays. These values are consistent with those found in the literature [24, 25]. An example of the method is shown in Figure 4(b).

The significance of the cross-correlation peaks depends on the assumed model for the light curves; we characterize this dependence using a Monte Carlo method [26]. In this method different power spectral density models can be compared with the data allowing for the selection of the best fit. We fit simple power-law models and study the source-to-source variability for the radio light curves.

4. Conclusions
We have presented data from the largest monitoring survey of radio sources that has been undertaken to date. A statistically rigorous analysis of the variability of different source populations has been performed, in which we find that gamma-ray loud blazars are intrinsically more variable at radio wavelengths than gamma-ray quiet blazars, that BL Lacs are more variable than FSRQs, and that there is a trend towards decreasing variability amplitude with increasing redshift for FSRQs. We have presented a method for assessing the significance of cross-correlations between radio and gamma-ray light curves.

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