

## Gamma-rays in the radio galaxy 3C 84: A complex situation

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3C 84 is a nearby Active Galactic Nucleus (AGN) that is unique in that it is believed that we are observing near the true jet launching region - unlike blazars. The source is active in  $\gamma$ -rays and has been detected with *Fermi* since its launch in 2008, including being detected at TeV energies with other instruments. Due to the relative proximity of the source ( $z=0.018$ ), it provides a unique opportunity to pinpoint the location of the  $\gamma$ -ray emission by combining the  $\gamma$ -ray data with very long baseline interferometry (VLBI) data. A study using the Korean VLBI network (KVN) showed that the  $\gamma$ -rays occur in both downstream jet emission and the region near where the jet is launched. Further analysis of the kinematics using Wavelet Image Segmentation and Evaluation (WISE) algorithm, which uses 2-dimensional cross-correlations to statistically derive the kinematics of high-resolution 7 mm VLBA data show that the  $\gamma$ -ray emission is caused by a fast-travelling shock catching a slower moving shock and then interacting with the external medium, in behaviour reminiscent of a long duration gamma-ray burst (GRB). This could explain why such high energy flaring is seen in such low Doppler boosted sources. Finally, we show some early results from a study of the jet launching region using the Global mm-VLBI Array (GMVA). The nucleus appears to have a consistent double nuclear structure that is likely too broad to be the true jet base.

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## 1. Introduction

3C 84 (the radio counterpart of NGC 1275) is a mis-aligned active galactic nucleus (AGN) located at the center of the Perseus cluster. As one of the brightest radio sources, it has a long history of study and has been known to be bright at radio wavelengths since at least the 1950s (Baade & Minkowski, 1954; Burbidge et al., 1963; Burbidge & Burbidge, 1965). The source is known to be two galaxies colliding and known to have large inhomogenous free-free absorption in the central region (Haschick et al., 1982; Walker et al., 2000; Fujita & Nagai, 2017).

The current radio morphology of the sub-parsec scale structure is shown in Fig. 1. The C1 region is thought to be at or near the location of the jet base, C3 is a slow moving feature and C2 is a quasi-stationary or very slow moving feature. While the source has been observed with Very Long Baseline Interferometry (VLBI) since the 1980s (e.g., Romney et al., 1984; Backer et al., 1987; Marr et al., 1989; Backer et al., 1987; Krichbaum et al., 1992), its radio brightness had been decreasing. However, since  $\sim 2005$ , the source has been rising in radio flux densities, apparently related to the ejection of a new component known as C3 from near the central super-massive black hole (SMBH) (Nagai et al., 2010). More recently the source has been detected in  $\gamma$ -rays and also at higher frequencies, possibly related to the interaction of the C3 region with the external medium (Nagai et al., 2014, 2017; Mirzoyan, 2016; Mukherjee & VERITAS Collaboration, 2016; Mirzoyan, 2017; Mukherjee & VERITAS Collaboration, 2017; Lucarelli et al., 2017). The nature of the radio emission and its connection with the  $\gamma$ -ray emission is an area of active study. In this proceeding, we briefly summarise the results of one submitted paper and two additional papers examining the  $\gamma$ -ray emission, high-resolution kinematics and morphology of 3C 84.

We have used a flat  $\Lambda$ CDM cosmology with  $H_0=69.6$  and  $\Omega_m=0.286$  (Bennett et al., 2014), which corresponds to a linear scale of  $1 \text{ mas} = 0.359 \text{ pc}$  at a luminosity distance of  $D_L=74.047 \text{ Mpc}$ .

## 2. Radio-Gamma correlations

Here we present some highlights from the upcoming paper (Hodgson et al. MNRAS, submitted). Variations in  $\gamma$ -ray emission from the *Fermi* LAT  $\gamma$ -ray telescope are compared with total intensity 1 mm data and monthly multi-frequency observations (at 14 mm, 7 mm, 3 mm and 2 mm) using the Korean VLBI Network (KVN). In this paper, our results show that there are large flares (particularly since 2015), short-time scale variability and a slow rising trend (see Fig. 2). The slow rising trend and large flares were located in the slow-moving C3 region. A discrete correlation analysis (DCF) of the  $\gamma$ -ray and total intensity 1 mm light-curves (see Fig. 3) found that they were highly correlated with an approximate 8 month lag. The data were interpolated and regridded to be analysed using a Pearson correlation coefficient. The large  $\gamma$ -ray flaring since 2015 was highly significantly correlated with the C3 region, however before 2015 the short time-scale variations were significantly correlated with the C1 region, showing that  $\gamma$ -rays could be associated both with the region near the SMBH (C1) and a travelling shock (C3).

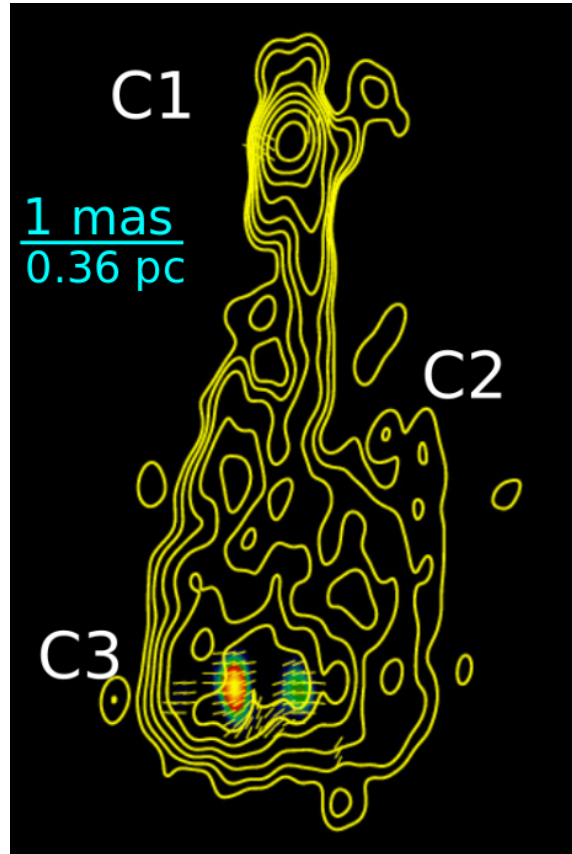


Figure 1: A recent (March 2017) map of 3C 84 adapted from public data available from the BU-VLBA-BLAZAR program, see Jorstad et al. (2017) for details. The contours are set at The broad emission regions C1, C2 and C3 are annotated. Colours denote polarised intensity. Contours decrease by a factor of  $\sqrt{2}$  from the peak flux density, with 1 mas corresponding to 0.359 pc.

### 3. Kinematic Analysis

In a further upcoming paper (Hodgson et al. in prep), the kinematics of the source was analysed using the Wavelet Image Segmentation and Evaluation (WISE) analysis package, which had previously been used to analyse the kinematics in M87 (Mertens & Lobanov, 2015, 2016; Mertens et al., 2016). This analysis revealed a highly complex kinematic structure. In a broad sense, non-ballistic component motions were detected, consistent with a sheath of a helical jet. The motion of C3, takes the appearance of “crashing through” the C2 region, which is itself revealed to be a very slow-moving jet component ejected in the early 1980s.

The WISE analysis shows that apparent super-luminal motion ( $\sim 1.2c$ ) are detected in the outer sheath of the jet, along the same trajectory as earlier slower moving shocks. When these faster shocks interact with slower moving shocks,  $\gamma$ -ray emission is seen. When these shocks then hit the external medium, even larger  $\gamma$ -ray flaring is seen. This behaviour appears to be reminiscent of the behaviour expected in a long-duration  $\gamma$ -ray burst (GRB). This could perhaps be an explanation for the so-called “Doppler crisis” where less Doppler-boosted sources are often seen at TeV energies,

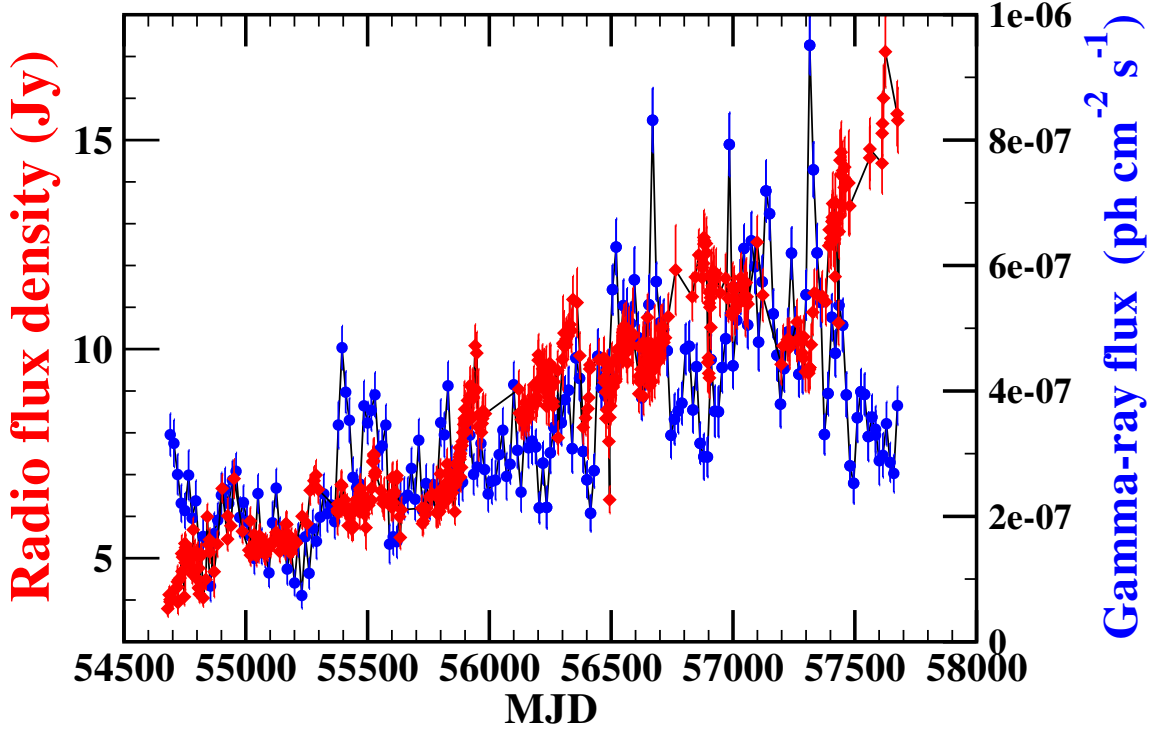


Figure 2: The total intensity light-curves of *Fermi*-LAT  $\gamma$ -ray (blue) and 1 mm data from the sub millimeter array (SMA) calibrator page (red) in 3C 84. The units of the Gamma-ray photon flux are in  $\text{ph cm}^2 \text{s}^{-1}$ .

whereas Doppler boosted “blazar” sources are less frequently detected (Jorstad et al., 2017).

#### 4. GMVA Analysis

We have additionally (Oh and Hodgson et al. in prep) analysed six epochs of 3C 84 using the Global mm-VLBI Array (GMVA, see Hodgson et al. (2016) for details). The source was observed between 2008 and 2016. These observations achieve angular resolution of greater than 50 micro-arcseconds, corresponding to a linear resolution on the order of  $\sim$ hundreds of  $R_S$ . In all epochs since 2008, we observe a double nuclear structure (C1a and C1b) separated by  $\sim 0.7$  mas, with a trend of increasing brightness temperature in the north-easterly and south-westerly directions. We find that the width of the 3 mm VLBI core is likely to broad to be the true base of the jet, or directly related to the accretion disk.

#### 5. Conclusion

We have shown that the  $\gamma$ -rays in 3C 84 occur in at least two different locations, including in the jet launching region and in travelling knots. Superluminal motion is for the first time detected in 3C 84 and is associated with  $\gamma$ -ray flaring when the fast shock “catches up” with a slower shock. Larger flaring including at TeV is then seen when these shocks interact with the external medium.

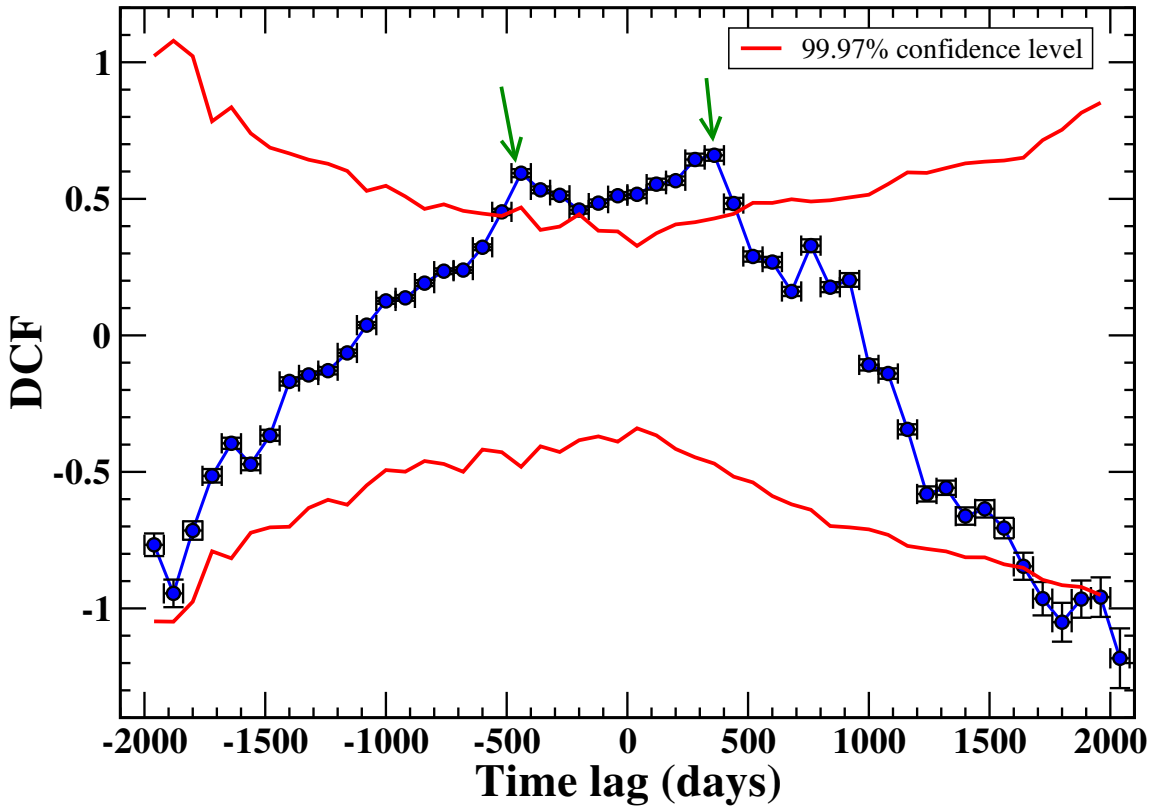


Figure 3: DCF of monthly binned  $\gamma$ -ray data with 1 mm total intensity radio light-curves.

This behaviour is similar to what is expected in long-duration GRBs, suggesting a possible solution to the ‘‘Doppler crisis’’. Additionally, the GMVA data suggest that the 3 mm VLBI core is likely not the true base of the jet.

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research made use of Astropy, a community-developed core Python package for Astronomy (Astropy Collaboration et al., 2013).

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