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A peculiar multiwavelength flare in the blazar 3C 454.3

Alok C. Gupta,^{1,2*} Arun Mangalam,³ Paul J. Wiita,^{4,5*} P. Kushwaha,^{6*} H. Gaur,¹ H. Zhang,⁷ M. F. Gu,¹ M. Liao,^{1,8} G. C. Dewangan,⁹ L. C. Ho,^{10,11} P. Mohan,¹² M. Umeura,¹³ M. Sasada,¹⁴ A. E. Volvach,^{15,16} A. Agarwal,² M. F. Aller,¹⁷ H. D. Aller,¹⁷ R. Bachev,¹⁸ A. Lähteenmäki,¹⁹ E. Semkov,¹⁸ A. Strigachev,¹⁸ M. Tornikoski¹⁹ and L. N. Volvach^{15,16}

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¹Key Laboratory for Research in Galaxies and Cosmology, Shanghai Astronomical Observatory, Chinese Academy of Sciences, Shanghai 200030, China

²Aryabhatta Research Institute of Observational Sciences (ARIES), Manora Peak, Nainital 263002, India

⁴Department of Physics, The College of New Jersey, PO Box 7718, Ewing, NJ 08628-0718, USA

⁸University of Chinese Academy of Science, 19A Yuquanlu, Beijing 100049, China

⁹Inter University Centre for Astronomy and Astrophysics (IUCAA), Post Bag 4, Ganeshkhind, Pune 411007, India

¹⁰Kavli Institute for Astronomy and Astrophysics, Peking University, Yi He Yuan Lu 5, Hai Dian District, Beijing 100871, China

¹¹Department of Astronomy, Peking University, Yi He Yuan Lu 5, Hai Dian District, Beijing 100871, China

¹²Shanghai Astronomical Observatory, Chinese Academy of Sciences, Shanghai 200030, China

¹³ Hiroshima Astrophysical Science Center, Hiroshima University, Kagamiyama 1-3-1, Higashi-Hiroshima 739-8526, Japan

¹⁴Department of Astronomy, Graduate School of Science, Kyoto University, Kitashirakawa-Oiwake-cho, Sakyo-ku, Kyoto 606-8502, Japan

¹⁵Radio Astronomy Laboratory of the Crimean Astrophysical Observatory, Katsiveli, Crimea 98688, Ukraine

¹⁶Taras Shevchenko National University of Kyiv, 4 Academician Glushkov Ave., 03127 Kiev, Ukraine

¹⁷Astronomy Department, University of Michigan, 311 West Hall, Ann Arbor, MI 48109-1107, USA

¹⁸Institute of Astronomy and National Astronomical Observatory, Bulgarian Academy of Sciences, 72 Tsarigradsko Shosse Blvd., 1784 Sofia, Bulgaria

¹⁹Aalto University, Metsähovi Radio Observatory, PO Box 11000, FI-00076 Aalto, Finland

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ABSTRACT

The blazar 3C 454.3 exhibited a strong flare seen in γ -rays, X-rays and optical/near-infrared bands during 2009 December 3–12. Emission in the V and J bands rose more gradually than did the γ -rays and soft X-rays, though all peaked at nearly the same time. Optical polarization measurements showed dramatic changes during the flare, with a strong anticorrelation between optical flux and degree of polarization (which rose from ~ 3 to ~ 20 per cent) during the declining phase of the flare. The flare was accompanied by large rapid swings in polarization angle of $\sim 170^{\circ}$. This combination of behaviours appears to be unique. We have cm-band radio data during the same period but they show no correlation with variations at higher frequencies. Such peculiar behaviour may be explained using jet models incorporating fully relativistic effects with a dominant source region moving along a helical path or by a shock-in-jet model incorporating three-dimensional radiation transfer if there is a dominant helical magnetic field. We find that spectral energy distributions at different times during the flare can be fit using modified one-zone models where only the magnetic field strength and particle break frequencies and normalizations need change. An optical spectrum taken at nearly the same time provides an estimate for the central black hole mass of $\sim 2.3 \times 10^9 \,\mathrm{M_{\odot}}$. We also consider two weaker flares seen during the $\sim 200 \,\mathrm{d}$ span over which multiband data are available. In one of them, the V and J bands appear to lead the γ -ray and X-ray bands by a few days; in the other, all variations are simultaneous.

Key words: galaxies: active – BL Lacertae objects: general – quasars: individual: 3C 454.3.

* E-mail: acgupta30@gmail.com (ACG); wiitap@tcnj.edu (PJW); pankaj. tifr@gmail.com (PK)

³Indian Institute of Astrophysics, Sarjapur Road, Koramangala, Bangalore 560034, India

⁵Kavli Institute for Particle Astrophysics and Cosmology, SLAC, Menlo Park, CA 94025, USA

⁶Department of Astronomy (IAG-USP), University of São Paulo, São Paulo 05508-090, Brazil
⁷Astrophysical Institute, Department of Physics and Astronomy, Ohio University, Athens, OH 45701, USA

1 INTRODUCTION

The flat spectrum radio quasar (FSRQ) 3C 454.3 (2251+158; z = 0.859) is a bright and frequently observed blazar. It shares the common FSRQ properties of non-thermal emission and significant variability across the entire electromagnetic spectrum along with substantial optical polarization (Smith et al. 1988; Healey et al. 2007; Sasada et al. 2013, 2014). FSRQs such as 3C 454.3 have spectral energy distributions (SEDs) that show the usual two broad humps peaking at mm-infrared (IR) wavelengths and around 1 GeV (Urry & Padovani 1995; Sambruna, Maraschi & Urry 1996). The lower energy one is ascribed to synchrotron emission from a relativistic jet pointing near our line of sight, while the high energy peak presumably arises from inverse Compton (IC) scattering of lower energy photons off the synchrotron emitting relativistic particles (e.g. Urry & Padovani 1995). The strongest constraints on emission models and the locations of emission regions in blazars can come from analysis of broad-band SEDs as they vary in time, and any clear correlations between different bands during flares are of particular interest. The central engine of 3C 454.3 contains a supermassive black hole (SMBH) estimated in the range 0.5- 1.5×10^9 M_{\odot} (Woo & Urry 2002; Liu, Jiang & Gu 2006; Sbarrato et al. 2012). The flow speed down the approaching relativistic jet is probably between 0.97c and 0.999c (Jorstad et al. 2005; Hovatta et al. 2009; Raiteri et al. 2011) and the angle to our line of sight is between 1° and 6° (Raiteri et al. 2011; Zamaninasab et al. 2013).

Several earlier multiband observations of 3C 454.3 have been conducted. Those including simultaneous γ -ray fluxes are of interest to us here, and as they must incorporate Fermi or AGILE data they must be relatively recent. In the observations of Bonning et al. (2009) excellent correlations between IR, optical, ultraviolet (UV) and γ -ray fluxes were seen, with lags within 1 d; however, the X-ray flux then was almost non-variable and not correlated with either the higher or lower frequency measurements. Vercellone et al. (2009) also saw correlated optical and high-energy γ -rays measured by AG-ILE; they had INTEGRAL and Swift X-ray measurements, though the latter were again not well correlated. More complete AGILEled multiband monitoring of 3C 454.3 over 20 months (Vercellone et al. 2010; Raiteri et al. 2011) found nearly simultaneous flux peaks across all bands from millimetre (mm) to γ -rays during the strong flares, with the γ -optical correlation usually having a time lag less than a day. Strong correlations between γ -ray and optical light curves (LCs) were found by Gaur, Gupta & Wiita (2012), though in that case, the γ -ray LC led the optical one by 4.5 \pm 1.0 d. Again, the X-ray LC was essentially constant and so showed no correlation with the other bands. Similar strong correlations were found between near-infrared (NIR)–optical and γ -rays by Kushwaha et al. (2017), but with *Fermi*-Large Area Telescope (LAT) γ -rays lagging the optical–NIR by \sim 3 d. While in this case the X-rays showed a behaviour similar to that observed in the optical-NIR, they were not well sampled. Strong correlated flux variability between Fermi γ -rays and 37 GHz radio flares have been seen on different occasions (León-Tavares et al. 2011; Ramakrishnan et al. 2015) in this blazar. The above studies of 3C 454.3 did not include optical polarization measurements.

A detailed multiband analysis of the variability of 3C 454.3 between 2009 and 2011 that did include some optical spectropolarimetry (Jorstad et al. 2013) discovered similar triple flare structures for each of three γ -ray outbursts. These correlations indicate that the locations and mechanisms are similar for all of those flares, the first one of which in 2009 December we revisit here with the incorporation of substantial additional optical photometry and polarimetry. Radio knots in the inner jet were associated with the first and third outbursts in mm-bands (Jorstad et al. 2013) and here we also include cm-band LCs. Other studies of this large flare of 3C 454.3 have included X-ray data from *Swift*-Burst Alert Telescope (BAT), *INTEGRAL*-Imager on-Board the *INTEGRAL* Satellite (IBIS) and HEXT and optical data from *Swift*-Ultraviolet and Optical Telescope (UVOT; Pacciani et al. 2010). Sasada et al. (2012) also studied this flare with a focus on optical polarimetric variations.

We now briefly note several multiband measurements of other blazars that incorporated optical polarimetry measurements. Another bright FSRQ that showed a γ -ray flare in *Fermi* observations during a multiband campaign is 3C 279 (1253-055; z = 0.536); Abdo et al. (2010) noted that it was coincident with a large change of optical polarization. In this instance the γ -ray flux peaked shortly before the optical and NIR fluxes and once again there were no significant simultaneous X-ray or radio variations at that time; however, there was a strong X-ray flare some 2 months later that might have had very modest optical/NIR and γ -ray counterparts. On another occasion in 2011 3C 279 was in a high γ -ray activity state that showed multiple peaks and coincided exactly with a 352° rotation of the optical polarization angle and flaring activity at optical bands (Kiehlmann et al. 2016). The prototype BL Lacertae object, BL Lac, has of course also been subject to a great deal of multiband monitoring. Marscher et al. (2008) made multiple very long baseline interferometry (VLBI) radio maps and optical polarization measurements and were able to detect a knot in the jet that apparently produced a double flare that emitted between optical and TeV γ -ray energies along with a radio outburst detected later. Another peculiar result for BL Lac was the discovery of a phase in its optical LC where the flux strongly anticorrelated with the degree of optical polarization (PD) while the angle of polarization stayed essentially fixed (Gaur et al. 2014). Finally, we mention multiwavelength [γ ray, optical and optical polarization, plus Very Long Baseline Array (VLBA)] variations of another bright BL Lac, S50716+714 (Larionov et al. 2013). They found rapid rotation of the linear polarization vector to coincide with a peak in both γ -ray and optical fluxes and that a new superluminal radio knot appeared at essentially the same time (see also Chandra et al. 2015).

In Section 2 of this paper we bring together γ -ray, X-ray, optical/NIR and radio flux measurements for 3C 454.3, along with optical polarimetry, during the period \sim MJD 55000–55200. During one substantial flare an apparently unique combination of flux and polarization changes was detected. In Section 3 we discuss models that could produce such observations.

2 DATA AND RESULTS

2.1 Gamma-ray fluxes

The LAT on the *Fermi Gamma Ray Space Telescope* (hereafter *Fermi*-LAT; Atwood et al. 2009) has been observing the γ -ray sky since its launch in 2008 June. The high sensitivity and wide field of view (~2.4 sr) of *Fermi*-LAT means that it has revolutionized our knowledge of the sky in its energy band that covers 20 MeV–300 GeV. *Fermi*-LAT normally operates in a scanning mode that covers the entire sky every 3 h.

The γ -ray LC of 3C 454.3 is shown in the top panel of Fig. 1. We extracted daily γ -ray fluxes in the 100 MeV–300 GeV energy range using the standard unbinned likelihood method implemented in the PYTHON likelihood library of the *Fermi* science tools version 10r0p5. Our analysis considers only the SOURCE class events tagged as 'EVCLASS=128, EVTYPE=3' under the PASS 8 instrument response



Figure 1. In the top and second panels γ -ray and X-ray fluxes from *Fermi*-LAT and *Swift*/XRT are, respectively, presented. The third panel gives optical position angle (PA) while the fourth gives the optical polarization degree (PD). In the fifth panel, we give optical V band data from KANATA, SMARTS and Steward as the lower LC along with NIR J-band data from KANATA and SMARTS as the upper one. In the bottom panel radio data are given from: UMRAO at 4.8, 8.0 and 14.5 GHz; CrAO at 22.2 GHz and Metsähovi at 36.8 GHz. Except where shown, error bars are smaller than the symbols. Solid vertical lines mark the three segments in which multiband correlations are studied and dashed vertical lines, respectively, mark the peaks of the first and second flares, the peak of the peculiar flare (PF) and a decaying phase of PF.

function P8R2_SOURCE_V6 from a circular region of interest (ROI) 15° centred on the source location. The Earth's limb γ -ray background was minimized by avoiding photons arriving from zenith angle of >90° while satellite operation and data acquisition quality was insured using filter '(DATA_QUAL>0)&&(LAT_CONFIG==1)'. The source model file was generated from the third *Fermi*-LAT catalog (3FGL-*gll_psc_v16.fit*; Acero et al. 2015) incorporating the Galactic and isotropic extragalactic γ -ray background by the respective templates *gll_iem_v06.fits* and *iso_P8R2_SOURCE_V6_v06.txt* provided by the LAT team. The effect of other sources outside the ROI was accounted by generating an exposure on an additional annulus of 10° around it. With all these inputs the likelihood fit was iteratively performed by removing point sources that were not contributing at the time and thus had a test statistic (TS; Mattox et al. 1996) <0 (Kushwaha, Singh & Sahayanathan 2014). We used a log-parabola model for the source with all parameters being free and the converged best fit was used to derive the photon flux.

2.2 X-ray fluxes

Swift X-Ray Telescope (XRT) data were gathered in the pointed Photon Counting (PC) and Windowed Timing (WT) modes. Most of the PC data have rates requiring pile-up correction while many WT data show varied position angles within one observation. We, thus, used the XRT data files generated from the online tools described by Evans et al. (2009) available at the UK Swift Science Data Center.¹ It corrects the products for bad pixels and columns, pile-up and field of view effects. Additionally, for finding the spectrum, this reduction also provides count-weighted auxiliary response and response matrix files accounting for the off-axis angle effects. The pile-up corrections for the PC data are done by using an annular source extraction region of varying inner radius depending on the rate. The resulting spectrum file for each observation was then modelled with the PHABS*POWER-LAW model in XSPEC (version 12.9.0i) with a fixed neutral hydrogen column density of 1.34×10^{21} cm⁻² (Villata et al. 2006). The unabsorbed flux between 0.3and10 keV was then calculated using the CFLUX task. The resultant LC is shown in the second panel of Fig. 1.

2.3 Optical/NIR photometry

We obtained photometric observations of 3C 454.3 from the Triple Range Imager and SPECtrograph (TRISPEC) instrument mounted on the 1.5-m 'KANATA' telescope at Higashi-Hiroshima Observatory. TRISPEC is able to perform simultaneous three-band (one optical and two NIR bands) imaging or spectroscopy along with polarimetry (Watanabe et al. 2005; Sasada 2012). The V- and J-band photometric data from the KANATA telescope are presented in red and cyan symbols, respectively, in the fifth panel of Fig. 1.

We also used the publicly available SMARTS² data where the observations are carried out on the 1.3 m telescope located at Cerro Tololo Inter-American Observatory with the A Novel Double Imaging Camera (ANDICAM) instrument. Data reduction and analysis of SMARTS data is described in Bonning et al. (2012). The *V*- and *J*-band SMARTS data are represented by the green and magenta symbols, respectively.

Finally, we also include optical V band public archival observations from Steward Observatory³ (Smith et al. 2009); these are represented by black symbols in the fifth panel of Fig. 1. As can be seen in Fig. 1 there is good agreement between measurements made at the different telescopes during times when more than one of these observatories obtained data.

2.4 Optical polarimetry

We obtained polarimetric observations of 3C 454.3 at the 1.5-m 'KANATA' telescope (Sasada et al. 2012). The polarization parameters are calculated from four consecutive images, which were obtained with half-wave-plate angles of 0° , 22.5, 45° and 67°.5. The instrumental polarization was less than 0.1 per cent in the *V* band. These data are presented in red symbols in the third (polarization angle, PA) and fourth (polarization degree, PD) panels of Fig. 1.

Sparser data from the Steward Observatory spectropolarimetric monitoring project (Smith et al. 2009) were previously published (Jorstad et al. 2013) and are also shown here (with black symbols) in the third and fourth panels of Fig. 1. There is excellent agreement

Table 1. Lag results for all the segments (in days).

Light curves	55060–55082 Segment 1	55082–55110 Segment 2	55150–55200 Segment 3			
γ versus XRT	$-0.24^{+0.80}_{-0.45}$	$-0.09^{+0.52}_{-1.80}$	$-0.32\substack{+0.58\\-0.54}$			
γ versus V	$-3.9^{+2.1}_{-1.6}$	$-0.2^{+0.4}_{-0.2}$	$+0.3^{+4.2}_{-1.1}$			
γ versus J	$-0.87^{+0.29}_{-2.11}$	$-2.2^{+2.1}_{-1.1}$	$+2.5^{+2.5}_{-1.9}$			
XRT versus V	$-5.6^{+2.4}_{-0.5}$	$+0.08\substack{+0.41\\-0.47}$	$+10.1^{+1.9}_{-3.5}$			
XRT versus J	$-5.4^{+1.8}_{-0.6}$	$-0.38\substack{+0.78\\-0.71}$	$+0.8^{+7.5}_{-1.8}$			
V versus J	$-0.02\substack{+0.20\\-0.20}$	$-0.05\substack{+0.38\\-0.28}$	$-0.86\substack{+0.69\\-0.14}$			
Flux versus PA for Segment 3 (55150-55200)						
γ versus PA	$-1.0^{+1.2}_{-3.2}$					
XRT versus PA	$-5.6^{+4.1}_{-1.1}$					
V versus PA	$+0.1^{+1.5}_{-0.2}$					
J versus PA	$-8.3^{+8.5}_{-0.8}$					

between the polarimetric measurements during the limited periods of overlap.

2.5 Radio observations

The 22.2 GHz radio observations of 3C 454.3 were carried out with the 22-m radio telescope (RT-22) of the Crimea Astrophysical Observatory (CrAO; Volvach 2006). Modulated radiometers were used in combination with the 'ON–ON' registration regime (Nesterov, Volvach & Strepka 2000). Radio observations at 36.8 GHz were made with the 14-m radio telescope (RT-14) of Aalto University Metsähovi Radio Observatory in Finland. A detailed description of the data reduction and analysis of Metsähovi data is given in Teraesranta et al. (1998). The observations and data processing techniques are similar for both RT-22 and RT-14. The results are given in the bottom panel of Fig. 1 in blue symbols for 22.2 GHz and magenta symbols for 36.8 GHz frequency.

Radio observations at 14.5, 8.0 and 4.8 GHz were obtained from the University of Michigan Radio Astronomical Observatory (UMRAO; Aller et al. 1999, 2014) that provided well sampled radio LCs at those frequencies for \sim 100 active galactic nuclei (AGNs) over time spans of \sim 30 yr.

2.6 Combined multiwavelength results

We show the multiwavelength (γ -ray, X-ray, optical, NIR, radio fluxes and optical polarization data) taken during MJD 54980– 55220 in Fig. 1. On visual inspection, three flares are seen and we focused our study on them. To search for cross-correlated variability, we selected three segments from the whole data presented in Fig. 1. Searching for cross-correlated variability, the discrete correlation functions (DCFs) were estimated using the z-transformed discrete correlation function (ZDCF; Alexander 1997, 2013) method, applicable to both uniformly and non-uniformly sampled data. The results for these three selected segments are reported in Table 1 and Fig. 2.

2.6.1 Segment 1 (MJD 55060-55082)

In Fig. 1, it is clear that there is a strong X-ray flare starting at \sim MJD 55060 and peaking at \sim MJD 55070 that then declines and reached a minimum flux state at \sim MJD 55082. To search for

¹ http://www.swift.ac.uk/user_objects

² http://www.astro.yale.edu/smarts/glast/tables/3C454.tab

³ http://james.as.arizona.edu/~psmith/Fermi/DATA/Objects/



Figure 2. DCFs for the three segments of the multiwavelength LCs of 3C 454.3 (see Fig. 1) between γ -ray versus optical (*V*), X-ray and NIR (*J*); X-ray versus optical (*V*) and NIR (*J*), and optical (*V*) versus NIR (*J*). The last panel shows the DCFs between LCs with PA and PD for the Segment 3. The vertical dashed line marks the zero lag between the two LCs (see Section 2.6).

multiwavelength cross-correlated variability for this flare we selected Segment 1 to correspond to MJD 55060–55082. On visual inspection, we noticed that there is no significant activity in optical fractional polarization and radio fluxes, so, for our examination of multiwavelength cross-correlated variability we only considered γ ray, X-ray, optical and NIR fluxes. The correlated variability results are plotted in the top left-hand panels of Fig. 2 and in Table 1. The results for this segment show simultaneous variation between the X-ray and γ -ray, and between the optical-V and NIR-J bands with peaks at zero lag. During this period the ZDCFs suggest a lag of \sim 3 d between the X-ray/ γ -ray and the V/J bands with V/J leading.

2.6.2 Segment 2 (MJD 55082-55110)

From Fig. 1, we also notice that there are nearly simultaneous γ -ray, optical/NIR flares starting at \sim MJD 55082 and peaking at

MJD 55092. This flare has poor temporal coverage in X-rays, though there is some evidence for an essentially simultaneous flare. There is only modest variability in optical polarization (which could be considered to show three small flares during that period, with one at the multiband peak and no evidence for changes in any of the radio fluxes. To search for multiwavelength cross-correlated variability for this flare we defined Segment 2 as MJD 55082–55110. Again we only considered γ -ray, X-ray, optical and NIR fluxes in our analysis of multiwavelength cross-correlated variability. The results are plotted in the top right-hand panel of Fig. 2 and in Table 1. The results for Segment 2 indicate simultaneous emission, with lags consistent with zero for all cross-correlations.

2.6.3 Segment 3 (MJD 55150-55200)

Our main focus in this paper is the strong peculiar flare (PF) noticed as peaking in the γ -ray and X-ray band at \sim MJD 55168 and declining to much lower flux states by ~MJD 55177 (see Fig. 1). To include the entire period of the activity in these bands we selected the Segment 3 to span MJD 55150-55200. On visual inspection, the γ -ray, X-ray, optical and NIR fluxes are strongly correlated during the flare period; however, these are anticorrelated with the PD during the decaying period of the flare between the vertical dashed lines in Fig. 1 and the PA goes through a large rotation during the flare. Our DCF analyses for Segment 3 are plotted in the bottom panels of Fig. 2; the left-hand panels give the multiwavelength flux correlations as discussed above, whereas the right-hand panels show fluxes against PA and PD. We did not use radio flux data in the cross-correlation analysis as the only significant activity seen is a nearly monotonic rise in the 36.8 GHz flux density that appears to have begun before this flare period and to continue afterwards. The flux correlation results for this segment suggest simultaneous emission with lags consistent with zero for fluxes in γ -ray, X-ray and optical/NIR bands, at least once the gap in V and J coverage towards the end of Segment 3 is taken into account. However, the PA/PD correlations with fluxes show significant anticorrelations for PA against all fluxes at zero lag, while the PD shows negligible correlations at zero lag with any of the fluxes and marginal indications for (see bottom right-hand panels of Fig. 2 and the bottom portion of Table 1).

As can been seen from the summary of previous work presented in the Introduction, the combination of such correlations has never been reported for this, or any other, blazar. We note that the optical/NIR flare starts earlier than do the X-ray and γ -ray flares, but the peak fluxes in all these bands are essentially cotemporal. The flare in X-ray and γ -ray lasts for ~ 10 d, which is the nearly same duration noticed in earlier γ -ray flares (Bonning et al. 2009; Vercellone et al. 2009; Gaur et al. 2012). Unless there is a rather unlikely coincidence, in the sense that the strong X-ray variation is independent of the other bands but just happened to coincide with them, these combined LCs strongly suggest that the dominant regions for optical through γ -ray production are cospatial. The PA rotations are also strong during the rising phase of the flare and during the post-flare phase, indicating that the region producing the large flux changes possesses a strong, dominant magnetic field direction, but one that is changing rapidly.

Unfortunately, the radio observations were rather sparse during the strong flare, but while our higher frequency radio LCs show slow upward trends that start before the flare and continue after it, there is no evidence for any rapid changes in these radio bands coincident with the strong flare; furthermore, the lower frequency radio LCs Table 2. SED parameters.

		Epoch		
Parameter	55019– 55023	(MJD) 55070	55168– 55169	55177
Particle index before break ^a	2.0	2.6	2.1	2.3
Particle index after break ^b	4.1	4.2	4.0	4.0
Magnetic field (G)	1.9	3.22	1.5	2.7
Equipartition fraction ^c	0.05	0.2	1	0.9
Doppler factor	12	17	16	16
Particle break energy	1114	594	706	662
Logarithm of jet power (erg s ^{-1})	45.5	47.2	46.8	46.5
Minimum particle energy	30	8	15	20

Note. Size of emission region: 5×10^{16} cm; maximum particle energy: 5×10^4 electron rest mass energy; torus covering factor: 0.3; IR-torus temperature: 1200 K.

^aFrom X-ray.

^bFrom optical–NIR (except for MJD 55019–55023).

^cParticle energy density/magnetic energy density.

are consistent with constant fluxes throughout this period. However, the 230 and 86 GHz LCs and 43 GHz VLBI measurements do show correlations (Jorstad et al. 2013). This type of behaviour is typical of blazar flares, where variations at cm-radio wavelengths usually lag those at optical and mm-bands, as can be explained by standard shock-in-jet models (e.g. Hughes, Aller & Aller 1985; Marscher & Gear 1985).

2.7 Spectral energy distributions

Fig. 3 shows SEDs at four epochs extracted from Fig. 1. The first is for a quiescent state (MJD 55019–55023), corresponding to the lowest brightnesses in optical–NIR along with a low γ -ray flux, although there were no X-ray data available then. The second is at the first significant rise in all bands (MJD 55070). The third epoch, from MJD 55168 to 55169, is at the peak of the PF for all of the γ -ray–NIR bands. For the final selected epoch, the SED is extracted from MJD 55177, during the decaying phase of the PF when the high-energy bands have nearly reverted to their pre-flare levels, whereas the optical and NIR emissions have barely begun to decay.

We model all the SEDs assuming a one-zone model with synchrotron and IC processes arising from a smoothed broken powerlaw particle spectrum with indices derived from the optical and X-ray data whenever available, following the approach of Kushwaha, Sahayanathan & Singh (2013). Those bands can be attributed to emissions from single components [synchrotron and synchrotron self-Compton (SSC), respectively] and thus directly reflect the particle spectrum. In contrast, the γ -ray spectrum appears to require inclusion of contributions from additional components: IC of the broad line region (BLR) photons and IC of IR photons from the torus around the central engine. During both these epochs, the flux changes significantly within a day in some bands, giving a reasonable constraint to the size of ~ 1 light-day ($\sim 5 \times 10^{16}$ cm). The resulting model fluxes are the curves plotted in Fig. 3 and the values of the model parameters are given in Table 2 (see Section 3 for more details).



Figure 3. Multiwavelength SEDs during: (left) a quiescent period from MJD 55019 to 55023 where it is lowest in all bands for which we have data and at the peak of the first flare; (right) and around the two epochs during the PF marked with dashed lines in Segment 3 of Fig. 1, corresponding to the peak and during the decline of that largest flare (see Section 2.7 for details).



Figure 4. Steward Observatory spectrum of 3C454.3. The continuum modelled with a single power law is plotted as a smooth dotted line. The residual emission line spectra after subtracting the power-law continuum are shown in the inset for the Mg II region with the lower two smooth curves (green), giving the modelled broad line components and the upper smooth curve (red), the entire modelled line profile.

2.8 Black hole mass estimation

Using different black hole (BH) mass estimation methods and multiwavelength data, the mass of the supermassive BH of the FSRQ 3C 454.3 previously has been estimated in the broad range of $0.5-4.5 \times 10^9 \,M_{\odot}$ (Gu, Cao & Jiang 2001; Woo & Urry 2002; Liu, Jiang & Gu 2006; Sbarrato et al. 2012). As we have focused on the multiwavelength flaring event during 2009 December 3–12 we downloaded a Steward Observatory archive optical spectrum of this blazar taken nearly simultaneously (on 2009 December 15). We

analysed this spectrum following the procedure given in Guo & Gu (2014) and the fitted spectrum is shown in Fig. 4.

We model the continuum as a single power law, with $f_{\lambda} \propto \lambda^{\alpha}$ and found the spectral index to be $\alpha = -0.680$. Also present is the broad emission line from Mg II that can be well modelled by combination of two Gaussian with full width at halfmaximum (FWHM) 3300 km s⁻¹. The BH mass is estimated using the broad Mg II line width and the continuum luminosity at 3000 Å $(\lambda L_{3000} = 8.64 \times 10^{46} \text{ erg s}^{-1};$ see Vestergaard & Osmer 2009). This gives us $M_{\rm BH} = 2.3 \ (\pm 0.5 \ \rm dex) \times 10^9 \ \rm M_{\odot}$. Our BH mass estimate is thus in agreement with previous results given the substantial errors present in all these methods.

3 DISCUSSION AND CONCLUSIONS

Several competing models have been used to explain the earlier flare events seen in multiwavelength observations of blazars. Here we will mention only some of those that have considered optical polarization properties to one degree or another. In most of the previous observations of blazars including polarimetry (e.g. Marscher et al. 2008, 2010; Jorstad et al. 2010; Sasada et al. 2010), a smooth rotation of the polarization angle with the rise in optical flux has been noticed on long-term polarimetric observations. This can be explained by a non-axisymmetric magnetic field distribution or a curved trajectory of the dissipation/emission pattern (e.g. Königl & Choudhuri 1985; Marscher et al. 2008). The large swings of polarization can be explained by a 'swinging jet' model where the angle the jet makes with our line of sight varies (e.g. Gopal-Krishna & Wiita 1992). However, in the simplest version of this model, involving only Doppler factor variations, the fluxes in all bands should change similarly, along with a swing in the in PA. That is not the case here: modest changes in optical-IR fluxes are seen along with substantial increments in X-ray and γ -rays. If variability arises from helical magnetic field structures, the observed polarization can be calculated following Lyutikov, Pariev & Gabuzda (2005) and Raiteri et al. (2013).

The degree and direction of visible light polarization changed drastically during the giant 20-d γ -ray flare in 3C 279 observed by Abdo et al. (2010). Their observations unambiguously connect the γ -ray and visible light emission regions, showing that they emerge from essentially the same location. They then argue that the changing polarization properties is indicative of motion in the jet: as a blob of gas flows around a bend in the jet, for example, the changing angle between the direction of the blob's motion and our line of sight can reproduce essentially the observed changes in the angle and degree of polarization. However, no explicit modelling was carried out to quantify this scenario.

Marscher et al. (2008) very nicely modelled the variations they observed in BL Lac during 2005-2006 by considering a shock travelling along a spiral path, and we now summarize their picture. It assumes that activity originating close to the BH inserts energy into a portion of the jet's area. This would be seen as a knot of emission as it propagates through both acceleration and collimation zones and the Doppler beaming of synchrotron emission grows as the knot accelerates along its spiral path (Marscher et al. 2008). In this model the knot's synchrotron output increases, producing the bulk of the emission from BL Lac from the optical through γ -ray bands until the disturbance exits the zone of helical path. The greatest beaming, and hence the strongest flare, in the LC occurs during the final spiral, when the Lorentz factor of the jet is very high and the velocity of the knot is closest to our line of sight. When the flare dominates the optical flux, we see the optical polarization vector rotate. Including projection effects and relativistic aberration in the model allows the optical PA data to be well fit and the similar PA seen at 7-mm VLBA measurements supports this picture. Owing to synchrotron self-absorption the first flare is not seen in the radio LCs. A second flare occurs when the knot crosses the radio core, which is identified with a standing shock by Marscher et al. (2008).

The relative constancy of the PA during these observations of 3C 454.3 in 2009, aside from during and immediately after the ma-

jor flare, implies that the above scenario was not being observed in this FSRQ at this time. However, recently Larinonov et al. (2013) have extended the Marscher et al. (2008) model to examine multiwavelength variations of a major flare in the blazar S5 0716+714. They note that minor flares often both precede and follow major optical outbursts. They interpret this in terms of oscillating Doppler beaming of the emission (e.g. Camenzind & Krockenberger 1992). In the Larinonov et al. (2013) picture, the series of flares occur when our viewing angle to the propagating shock wave is smallest. Many different flux and polarization behaviours could be reproduced if the large number of parameters of the model are varied appropriately (Larinonov et al. 2013).

Recently, Mohan & Mangalam (2015) presented a fully relativistic [including gravitational redshift (GR) effects] model of variability in AGN by considering synchrotron emitting blobs in helical motion along a funnel or cone-shaped magnetic surface anchored to the accretion disc near the BH. The simulated LCs for the Mohan & Mangalam (2015) model include light bending, time delay and aberration, as well as both Doppler and gravitational shifts. They find that the beamed intensity has a systematic phase shift with respect to that from the simpler special relativistic model of Camenzind & Krockenberger (1992). The results indicate that a realistic magnetic surface geometry in a general relativistic framework is needed to describe how orbital features in the jet change the observed emission, at least in the vicinity of the BH. For these unique observations of 3C 454.3, the critical results we need to explain are the systematic changes in the PA and in the polarization fraction during the modest change in optical-IR flux. A model along the lines of Mohan & Mangalam (2015) takes advantage of GR effects when the source is close to the BH and so bends, as invoked, e.g. by Abdo et al. (2010), can explain the optical PA variation. But it also exploits the helical path to explain the PD variation (e.g. Marscher et al. 2008; Larianov et al. 2013) and so has a better chance of explaining this complicated behaviour.

The overall boost factor g is given by (see Mohan & Mangalam 2015)

$$g = \frac{E_{\rm obs}}{E_{\rm em}} = (1 - 2M/R)^{1/2} D = \frac{(1 - 2M/R)^{1/2}}{\Gamma(1 - \beta \cos \xi)},$$
 (1)

where *M* is the BH mass, *R* is the distance (in mass units), *D* is the Doppler factor, Γ the bulk Lorentz factor of the blob, while ξ is the angle between the direction of the photon to the observer and the instantaneous velocity of the blob. The fact that the optical flux does not seem to change much indicates the near constancy of ξ for the given viewing angle. For an appropriate choice of model parameters, as observed from GR simulations in a conical geometry, the LCs can flatten out (see fig. 11 in Mohan & Mangalam 2015).

We can take the blob to be equivalent to a minijet having a constant rest-frame emission and polarization properties that is following a bent helical path. The observed degree of polarization for synchrotron emission coming from the region of helical magnetic fields is found using $P = P_{\text{max}} \sin^2 \chi'$, where χ' is the viewing angle in the jet rest frame. This angle and the observed viewing angle, χ , are related through the Lorentz transformation:

$$\sin \chi' = \frac{\sin \chi}{\Gamma(1 - \beta \cos \chi)},\tag{2}$$

where, as usual, Γ is the bulk Lorentz factor of the plasma. Note that while the built-in GR features of this fully relativistic model are particularly useful for time keeping, with respect to the clock of a distant observer, of the trajectory of blobs starting from near the BH, the kinematic effects themselves are negligible when $r \gg r_g$.

As discussed in Lyutikov & Kravchenko (2017), the plane of polarization rotation lies in the projection of plane formed by line of sight and the velocity field on the sky and so the PA rotation can result from changes in magnetic field topology or Doppler boosting or a combination of these. On the other hand, the lag of γ -ray emission behind the NIR-optical output, which has been observed in this source during other episodes (e.g. Kushwaha et al. 2017), can result from a steeper decline of the external radiation field as compared to the magnetic field, as argued by Hayashida et al. (2012) and shown by Janiak et al. (2012). Further, a zero lag between X-rays and γ -rays, but both lagging with respect to the NIR–optical strongly suggests that the X-ray emission has a substantial contribution from the process dominating the γ -ray band. Thus, a time-dependent model is required to actually understand the relative effect for both these situations. However, SED modelling can still be used to understand the observation by exploring the relevant quantities expected to cause such variation. In the SEDs displayed in Fig. 3 those corresponding to the peak and decay portions of the PF show essentially no change in optical-IR fluxes while X-rays and γ -rays both show substantial changes. At the same time, the PA rotates by 180°. The SED for the first flare, on the other hand, shows a substantial hardening at X-rays with a relatively steeper γ -ray spectrum compared to the PF, while the quiescent SED provides some evidence for the presence of a thermal bump in the optical-UV and displays a steeper γ -ray spectrum compared to the others.

In FSRQs, within the framework of a one-zone leptonic origin of the synchrotron emission, the explanation of γ -ray spectra requires external Comptonization and can have contributions from multiple photon fields such as the BLR and/or torus, depending on the location of the emission region along the jet. Because of contributions from multiple components, the γ -rays can exhibit different spectra while the IR–optical region may have an essentially constant spectral slope. Further, as the IR–optical component is synchrotron emission, the observed spectrum is directly related to the relativistic particle spectra and in this case the IR–optical (except when a thermal (accretion disc) bump contaminates this regime (as may be the case here for the quiescent SED) and X-ray spectra can be used to obtain the particle indices. With this, the relative contributions of external IC from the BLR and IR regions can be determined by reproducing the γ -ray emission, if the IR temperature is known.

We wish to gain insights into the physics using a minimal number of variations in the parameters that can give rise to SEDs that are consistent with understanding the PA rotations during the PF and the observed lag during the PF, with the optical-NIR changes leading the X-ray/ γ -ray ones. Hence we fixed the IR to a 1200 K blackbody with a covering fraction of 0.3 as inferred for the FSRQ PKS 1222+216 (Malmrose et al. 2011). Parameters able to reproduce the observed SEDs are given in Table 2 and the model fluxes for them are as shown in Fig. 3. This SED modelling alone can only constrain the magnitude of the magnetic field and not its direction (hence, not the PA). However, the only changes needed to explain the essentially constant fluxes in the optical/IR and the very different fluxes in the X-ray and γ -ray parts of the SED involve B, the particle normalization (which can be derived from the equipartition factor given in Table 2) and the particle spectrum before the break. So if there is no change to the Doppler factor, then the change in the strength and orientation of B is required to occur in such a way that it does not affect the overall emission in the low-energy portion of the SED (e.g. Joshi, Marscher & Böttcher 2016) and can also give rise to a hardening of the particle spectrum with a Doppler to bulk Lorentz factor ratio of \sim 1.6. On the other hand, the SED of the first flare is dominated by the magnetic field, with

X-rays resulting from external Compton (EC), in contrast to the PF where the X-rays are mainly from SSC. For the quiescent SED, the NIR–optical portion is modelled as containing both synchrotron and thermal disc emission associated with the mass of SMBH derived here ($\sim 2.3 \times 10^{10} \, M_{\odot}$). However, most of the physical parameters are uncertain for the quiescent SED as substantially less data were available then. Furthermore, it should be noted that the modelled thermal bump from an accretion disc is an upper limit so that its signature is not visible in the other three flare SEDs.

An improved model for synchrotron polarization in blazars, involving three-dimensional radiation transfer and assuming a standard shock-in-jet explanation for the flare in a jet with an originally dominant helical magnetic field, recently has been developed (Zhang, Chen & Böttcher 2014, 2015). These simulations can reproduce the range of polarization behaviours seen during earlier flares without requiring either bent or helical jet trajectories (e.g. see Chandra et al. 2015).

From approximately MJD 55080-55165, the PA generally stays at the same value, while the PD rises and falls. These changes in PD are coupled with some smaller flares in multiple bands as well. These changes are likely to arise from shock compression and acceleration. For example, Laing's (1980) model argues that an increase in PD is due to the shock compression of a turbulent field (cf. Marscher 2014); however, PA variations associated with such a field can be erratic. In our data, especially the portion from MJD 55120 to 55130, where the PA has nearly no variation while the PD increases from \sim 5 to \sim 15 per cent, it appears that the PA variation is not as erratic as expected from a turbulent field. So we suggest that the background field indeed is likely to be generally dominated by the toroidal component of a helical magnetic field (Zhang, Chen & Böttcher 2014, 2015). This is also suggested in the study by Jorstad et al. (2013) where it was observed that the quiescent state of 3C 454.3 during the current observation period was associated with the alignment of the optical polarization PA with the jet opening angle and was interpreted in terms of a well-ordered toroidal magnetic field. When a shock compresses the toroidal component, the PD will increase while the PA generally stays the same and the radiation of this entire period may be from the same emission region. From MJD 55165 to 55185, the PA completes a 180° rotation, accompanied by a strong variation in PD. This is probably due to some significant change in the emission region and it is very reasonable to suppose that reconnection may happen inside the emission region. In that case the toroidal field component is dissipated and the reconnection strongly accelerates particles, leading to strong flares extending up to the X-ray and γ -ray bands. Meanwhile, the poloidal component becomes dominant and triggers a PA rotation and PD variation. Afterward, the emission region recovers to its initial magnetic topology.

In AGN jets the electric vector position angles (EVPAs) on parsec scales tend to have polarization orthogonal to the jet in radio-loud quasars, while BL Lac objects usually evince polarization along the jet (e.g. Lyutikov, Pariev & Gabuzda 2005). The basic shock mechanism produces fields compressed in the shock plane and so for transverse shocks it naturally yields EVPAs along the jet. However, as shocks are normally intrinsically transient events, it is difficult to see how the jet could retain its polarization orientation over extensive distances. In addition, since internal shocks in relativistic jets normally are oblique (e.g. Hughes 2005), the bimodal distribution of jet EVPAs between the AGN classes is unexpected. Hence, the EVPAs in BL Lacs seem to be in disagreement with the basic shock model. An alternative interpretation of the jet polarization, which we favour, is that the flow carries large-scale helical magnetic fields. The polarization properties of a relativistic jet carrying helical magnetic fields can both reproduce the average properties of the jet polarization and the bimodal distribution of the observed EVPAs (Mangalam, in preparation).

By our combining γ -ray, X-ray, optical, NIR and radio monitoring of the FSRQ 3C 454.3 in ~MJD 55000–55200 with optical polarimetric data we have found a flare with apparently unique characteristics. The flare is essentially simultaneous from γ -ray down to NIR energies, which is relatively uncommon, and the polarization behaviour is also unusual. Clearly, additional simultaneous multiband observational campaigns addressed at both FSRQs and BL Lacs that also include polarization measurements are necessary for a better understanding of the location and physical mechanisms behind the variety of variations in blazars.

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