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Observations of the flaring *Fermi*-LAT blazar 4C +01.02 and prospects in spectro-polarimetry with SALT-RSS

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The *Fermi* Gamma-Ray Space telescope has identified 1741 active galactic nuclei during its first four years of observation (2008–2012) and detected 1145 blazars and 573 blazar candidates of uncertain type (BCUs) as listed in the Third *Fermi*-LAT Point Source Catalog (3FGL). Since *Fermi* typically operates in survey mode, sources from the whole sky are monitored almost continuously. Daily or sub-daily *Fermi*-LAT binned light-curves of bright blazars above 100 MeV can be produced for any given time range since August 2008. It is thus possible to identify flaring periods of blazars and trigger observations with South Africa-based optical telescopes to perform γ-ray *versus* optical correlation studies of flux variability. Also, the recently commissioned polarisation capability of the Robert Stobie Spectrograph (RSS) on the 10-meter class *Southern African Large Telescope (SALT)* at the *South African Astronomical Observatory (SAAO)*, Sutherland, is expected to contribute to the characterisation of the wavelength dependent radiation emission mechanisms of these objects. We report our preliminary studies on the blazar 4C +01.02 and discuss the prospects for spectro-polarimetry of a broader sample of flaring blazars.

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PoS(HEASA 2016)021

1. Introduction

The Large Area Telescope onboard the *Fermi* Gamma-Ray Space Telescope (*Fermi*-LAT), operating since 2008, is sensitive to γ-ray photons between $\sim$ 20 MeV and $>$ 300 GeV [1]. Among the 1591 sources of the Third *Fermi*-LAT AGN Catalog (3LAC) [2], constructed using the first four years of *Fermi*-LAT data (3FGL [3]), 1559 objects are classified as *blazars* (632 BL Lacs, 467 flat spectrum radio quasars [FSRQs], and 460 blazar candidates of uncertain type [BCUs]). Operating in survey mode for most of its observation strategy, *Fermi* is able to provide a consistent monitoring of the whole sky every three hours.

Several South Africa-based optical telescopes are used for joint optical/γ-ray observations of blazars during outbursts. Most of them are based near Sutherland (32° 23' 14" S, 20° 48' 42" E; altitude:1798 m), the main observation site of the *South African Astronomical Observatory (SAAO)*. We use the *Robert Stobie Spectrograph (RSS)* on the 10-m *Southern African Large Telescope (SALT)* [4, 5, 6] for optical spectroscopy with good sensitivity for blazar observations. Due to the design of the telescope, observations with SALT-RSS are constrained to be performed for sources within the $-75°$ to $+10°$ declination range. We also use the *SpUpNIC spectrograph* [7] on the 1.9-m *Radcliffe* Telescope, based on the same site. The *Boyden* Observatory (29° 02' 19.7" S; 26° 24' 17.0" E; altitude:1372 m) of the University of the Free State, near Bloemfontein, also hosts the Boyden 1.5-m Telescope and the Irish *Watcher Robotic Telescope*.[1] Both these telescopes are used for photometric observations. Besides the project presented in this paper, more details on our blazar programmes using *Fermi*-LAT and South Africa-based telescopes can be found in [8, 9, 10].

Blazar 4C +01.02 (PKS B0106+013) is a distant FSRQ (radio coord.: R.A.=01h 08m 38.8s, Decl. =+01° 35' 00"; redshift z=2.099) monitored by *Fermi*[2] and the radio *Very-Long-Baseline Interferometry (VLBI)* under the *MOJAVE* project.[3] Kharb et al [11] presented an interesting multi-wavelength study of the source in 1988–1989, using data from the *Hubble Space Telescope (HST)*, MOJAVE and the *Chandra* X-ray space telescope. Following *Fermi*-LAT reports on outbursts in March/April 2016, we started optical monitorings of 4C +01.02. We also performed spectroscopic observations with both SpUpNIC and SALT-RSS.

We present a time-domain study of 4C +01.02 in Section 2, then our project using spectroscopy and spectro-polarimetric observations from South Africa-based telescopes in Section 3, and our conclusions in Section 4.

2. Time-domain study of FSRQ 4C +01.02

We analysed *Fermi*-LAT data from 11 May till 15 August 2016 (MJD 57519–57615), in the 100 MeV–300 GeV range, using the Pass 8 data representation and the *Fermi* Science Tools version v10r0p5.[4] We produced one-day binned light-curves using the unbinned likelihood algorithm (gtlike/pyLikelihood Science Tool) with the following standard analysis cuts applied to point

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[1] http://watchertelescope.ie

[2] http://fermi.gsfc.nasa.gov/ssc/data/access/lat/msl_lc/

[3] http://www.physics.purdue.edu/MOJAVE/sourcepages/0106+013.shtml

[4] http://fermi.gsfc.nasa.gov/ssc/data/analysis/

PoS(HEASA 2016)021

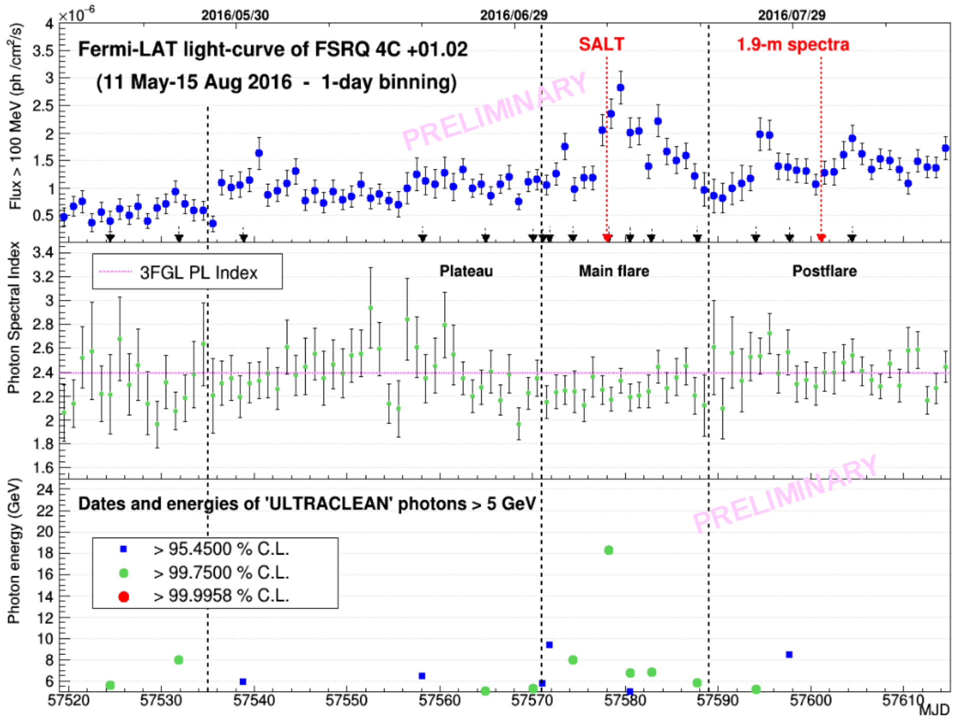

Figure 1: Upper panel: *Fermi*-LAT light-curve of 4C +01.02 above 100 MeV between 11 May and 29 August 2016 in one-day binning. Vertical dashed lines indicate separations between three phases of the outburst: plateau, flare and postflare, whose spectral parameters are presented in Table 1. Black arrow indicated the arrival time of photons above 5 GeV. Middle panel: Optimised value of the photon index of the source. The magenta horizontal dashed-line indicates the value of the PL photon index of 3FGL. Lower panel: Arrival time and energies of high energy photons ("ULTRACLEAN" photon class, $>$ 5 GeV). Three levels of confidences of the association of the photon with 4C +01.02 are indicated.

Table 1: Spectral parameters obtained by running the likelihood analysis over four periods of this outburst. We model the spectral shape of 4C +01.02 by a the power-low function (PL — characterised by the photon index Γ), then by a log-parabola (LP — characterised by the α and β parameters. What is labeled as "preflare" (MJD 57519-57571) is also characterised by a hardening of the PL photon index (Γ).

Period	Γ	α	β	Flux (ph cm^{-2} s^{-1})
11 May-28 May (Pre-flare)	2.26 $\pm$ 0.06	2.04 $\pm$ 0.09	0.19 $\pm$ 0.06	5.35e-07 $\pm$ 4.38e-08
28 May-02 Jul (Plateau)	2.36 $\pm$ 0.03	2.27 $\pm$ 0.04	0.11 $\pm$ 0.03	9.94e-07 $\pm$ 3.50e-08
02 Jul -20 Jul (Flare)	2.26 $\pm$ 0.03	2.11 $\pm$ 0.04	0.16 $\pm$ 0.03	1.56e-06 $\pm$ 5.71e-08
20 Jul -15 Aug (Postflare)	2.41 $\pm$ 0.03	2.32 $\pm$ 0.04	0.12 $\pm$ 0.03	1.38e-06 $\pm$ 4.40e-08

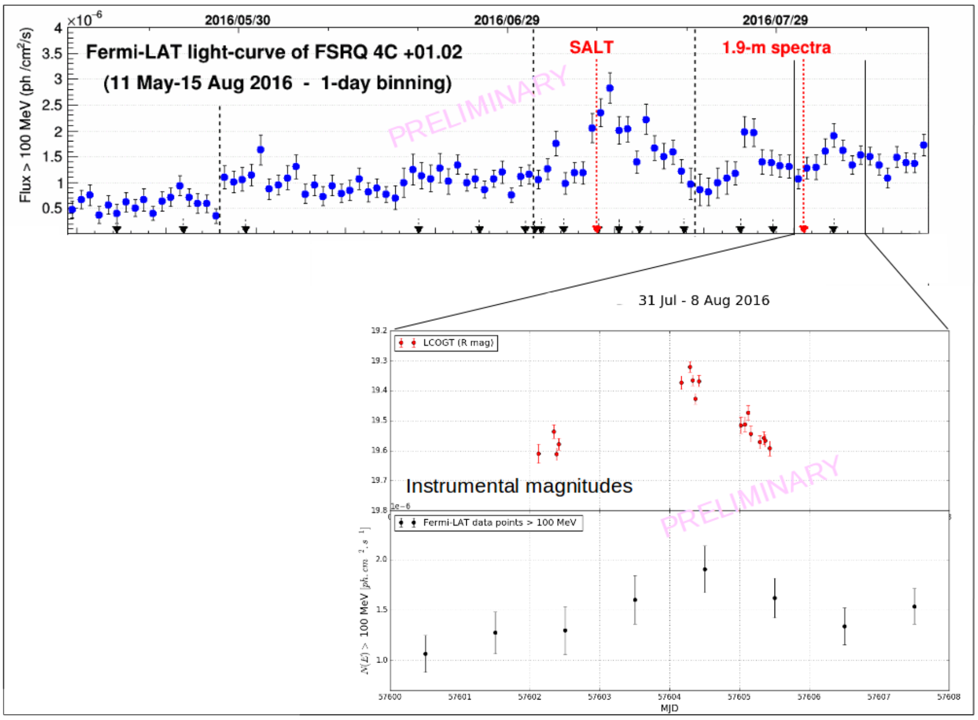

Figure 2: *Fermi*-LAT light-curve of 4C +01.02 above 100 MeV between 11 May and 29 August 2016 in one-day binning, as in Figure 1. The lower panels contain a zoom on the *Fermi*-LAT light-cuve during 31 July–8 August 2016, compared to the optical light-curve with LCO in the R-band.

source analysis: radius of the *Region of interest* (ROI)=15°; Source region=ROI+10°; SOURCE class; event type = 3; zenith angle $< 90°$; DATA_QUAL=1, LAT_CONFIG=1; Diffuse emission: `gll_iem_v06.fits` (Galactic) and `iso_P8R2_SOURCE_V6_v06.txt` (extragalactic) templates. The source of interest is modeled by a single power law (PL) of photon index Γ. Eight parameters defining the spectral shapes of the brightest point sources of the ROI and the two diffuse templates are kept free in the likelihood analyis.

We present in Figure 1 the daily light-curve of 4C +01.02 (upper panel). According to the flux level and variability, we defined four episodes that we refered to as *pre-flare*, *plateau*, *(main) flare* and *postflare*, sucessively. In Table 1 are presented the spectral parameters optimised during the likelihood analysis of our data for each of the four episodes, using successively the PL and log-parabola models. The *plateau–flare–post-flare* pattern was previously observed for FSRQ 3C 454.3 during several of its outbursts (eg Britto et al [12] and references therein). The dates of observations with SALT and the 1.9-m telescope are labeled in red. The variation of the spectral photon index Γ (middle panel) shows evidence of hardening when the source is brighter — during the main flare. This is a common feature reported for bright FSRQs during outbursts. An unusual feature is that the pre-flare period (corresponding to a relatively quiescent state of the source) is also characterised by a hardening of the spectrum, as also reported in Table 1.

High cadence monitoring of 4C +01.02, with short exposure times, was performed with the

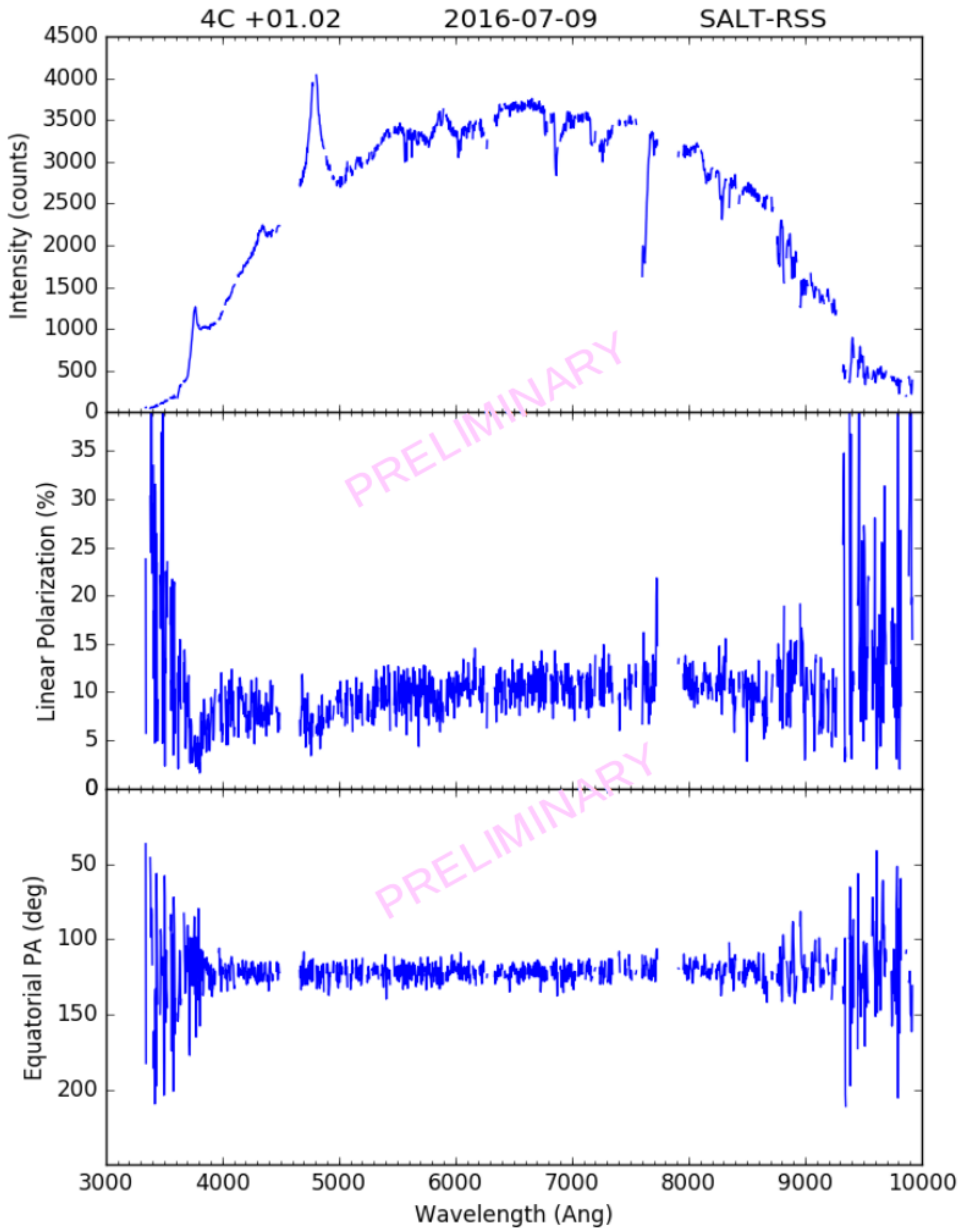

Figure 3: 4C +01.02 SALT-RSS count spectrum in the 3500–10000 Å range (grating PG0300) and polarised parameters, obtained on 9 July 2016 (3:15–3:56 UT), combining four exposures of 600 s each.

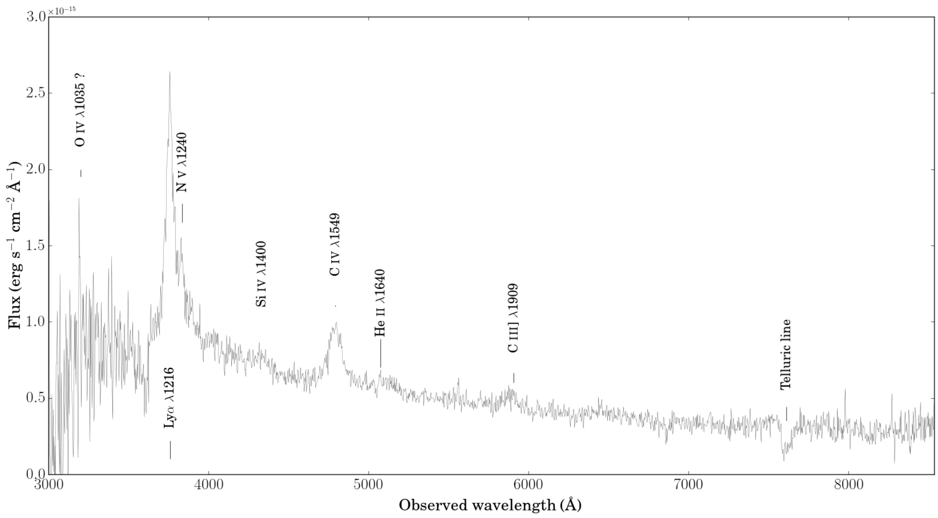

Figure 4: 4C +01.02 spectrum from SpUpNIC (1.9 m telescope/SAAO/Sutherland) in the 3000–8500 Å range, taken on 1 August 2016, at 2:30 UT, combining two exposures of 600 seconds, grating 7.

Las Cumbres Observatory (LCO) global network of telescopes[5] during 2–5 August 2016 (MJD 57602–57605). Monitoring continued with both the LCO instruments and the Watcher telescope for several weeks beyond these dates. We present in Figure 2 a highlight of the 31 July–8 August (MJD 57600–57608) period of the *Fermi*-LAT daily light-curve (lower panel), along with our first LCO data, presented in this figure for the R-band only (upper panel). Data collected during a longer period and in the B and V bands are expected to be presented in Britto et al [13]. Also, near simultaneous and complementary observations by Watcher and the 1.5-m Boyden telescope are still being processed. However, the preliminary data presented in Figure 2 gives a first insight of a day-scale correlation between optical and γ-ray light-curves.

3. Perspectives of spectroscopy and polarimetry measurements with SALT-RSS

Constraining the physical processes that power blazar jets is a current challenge, though the unified model of AGN [14] provides a basic picture concerning the emission of non-thermal radiation. Radiation is expected to be emitted at different distances from the central supermassive black hole, depending on its frequency. If absorption of radiation can be observed, it may constrain the location (or locations) of this emission. Also, the nature of the non-thermal X-ray and γ-ray emission remains to be understood (leptonic *versus* hadronic scenarios). Among the methods used for all these investigations are the monitoring of fast variability [15, 12, 8], absorption of γ rays in the broad-line region (BLR) [16, 17, 18] and the measurement of polarisation [19]. In particular, the measurement of optical polarisation allows constraints on the strength and geometry of the magnetic field of the AGN (linear polarisation), and constraints on the location of the γ-ray emiting region (polarisation angle change — see Trippe [19] and references therein).

[5] previously called LCOGT, https://lco.global

A recent feature of SALT-RSS is the polarimetry capability [20]. We have collected spectro-polarimetry data with SALT-RSS from blazar PKS 2023-07, 4C +01.02 and PKS 1510-089. The spectrum of 4C +01.02 (obtained on 9 July 2016) is presented in Figure 3 (upper panel) along with the measurements of the linear polarisation and polarisation angle as a function of the wavelength (middle and lower panels respectively). This spectrum was obtained during the γ-ray *main flare* reported in Section 2). We note a polarisation degree in the 5–10 % interval, remaining quite stable on the whole wavelength range. The dip around 3700–3800 Å corresponds to the position of the Lyα 1216 Å line, where the percentage of thermal radiation is higher. However, further studies are needed to discard eventual instrumental/analysis systematic effects. The polarisation angle also remains constant.

An optical spectrum of 4C +01.02 in the 3000–8500 Å range was taken with the SpUpNIC spectrograph of the SAAO 1.9-m telescope, on 1 August 2016 (Figure 4). This spectrum was taken during the *post-flare* phase of the outburst, when the γ-ray flux was about half what it was during the SALT-RSS acquisition, as indicated in Figures 1 and 2. We also expect to reduce additional observations that were performed at later stages in order to monitor and quantify the spectral changes in 4C +01.02 during different phases of the outburst.

Other flaring blazars are also being observed with SALT-RSS and SpUpNIC, and similar studies are expected to be undertaken, specifically multi-wavelength studies of lower redshift blazars as potential targets for TeV telescopes and the upcoming *Cherenkov Telescope Array* (CTA) [21, 22, 23, 10].

4. Conclusions

We have observed FSRQ 4C +01.02 over several months (and continued till early December 2016) and were able to report the γ-ray variability pattern of the source during the May–August 2016 period, for which we got quasi-simultaneous optical observations. A correlation between the R and high energy spectral bands was observed within a common limited range. The sensitivity of the SpUpNIC spectrograph and SALT-RSS give interesting perspectives to monitor the temporal variability of both the spectrum and polarisation parameters of 4C +01.02. Spectro-polarimetic measurements of this source and other flaring blazars at different phases during outbursts are expected to constrain models of radiation production mechanisms that power the blazar engine.

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PoS(HEASA 2016)021

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