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Studies of optical/gamma-ray flares of blazar 4C +01.02: recent updates from the 2016-2017 observations*

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The flat spectrum radio quasar 4C +01.02 became one of the brightest active galactic nuclei detected at high redshift ($z = 2.1$) in gamma rays when it underwent a series of outbursts during several months in 2016. We monitored this source in gamma rays using the Large Area Telescope onboard of the *Fermi* spacecraft (*Fermi*-LAT), and in optical using the Las Cumbres Observatory (LCO). The highest peak flux detected was $F(E > 100\ \mathrm{MeV}) = (2.8 \pm 0.3)\ 10^{-6}\ \mathrm{ph\ cm^{-2}\ s^{-1}}$ on 10 July 2016 (MJD 57579, daily average). We also obtained optical spectropolarimetry with the Robert Stobie Spectrograph on the Southern African Large Telescope (SALT-RSS) and observed a degree of linear polarisation of up to 10% during flaring states, and ∼1% during a quiescent period. We report recent updates we obtained in our time-domain and spectral studies of this source in July–August 2016, November–December 2016, and July 2017.

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*based on observations made with the Southern African Large Telescope (SALT)
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1. Introduction

The flat spectrum radio quasar 4C +01.02 (PKS B0106+013) is a high redshift blazar (optical coord: R.A. = 01h 08m 38.8s, Decl. = +01° 35' 00", $z = 2.099$). This source has shown two relatively bright outbursts, in April and November 2016. Near-simultaneous optical data were obtained in optical and gamma rays.

Multiwavelength observations of flaring blazars can provide information on particle acceleration occurring in the relativistic plasma jets [4]. Optical polarisation and spectropolarimetry (wavelength dependent polarisation) are crucial tools to probe the ratio of synchrotron radiation (polarised) from the jet over thermal radiation (unpolarised) emitted by radiation fields surrounding the central supermassive black hole of the AGN. Such radiation fields are the ultraviolet-blue emission from the disk and the broad-line region (BLR), the red emission from the host galaxy and the infrared emission from the dust torus. Furthermore, the degree of order of the magnetic fields surrounding the emitting region can be constrained through spectropolarimetry ([3] and references therein).

We present in this paper updates on our on-going study of 4C +01.02 during its 2016 long lasting outburst [5], using new observational data collected from August 2016 to July 2017. We used the *Fermi*-Large Area Telescope [1], the Southern African Large Telescope–Robert Stobie Spectrograph (SALT-RSS) [7, 10] and the Las Cumbres Observatory (LCO) [6]. Details on these intruments and on the data reductions are given in [5].

We present our updated gamma-ray and three-band filter optical light-curves in section 2, followed by the SALT-RSS observations in section 3. Finally, we conclude with the summary of the status of our project in section 4.

2. Gamma-ray/optical light-curves

We analysed *Fermi*-LAT data from 20 October 2014 to 28 April 2017 (MJD 56954–57871), in the 100 MeV–300 GeV range, using the Pass 8 data representation and the *Fermi* Science Tools version v10r0p5[1], running the unbinned likelihood algorithm (gtlike/pyLikelihood Science Tool) with the following standard analysis cuts applied to point 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. We used the user contributed `make3FGLxml.py` script[2] to prepare the source model from the *Fermi*-LAT Third Source Catalog (3FGL, [2]).The source of interest was modelled by a single power law (PL). We produced a three-day binned *Fermi*-LAT light-curve for this whole period, plotted in Figure 1 (upper panel), where the four SALT-RSS observations taken during high gamma-ray states are indicated with dashed-red arrows. In the middle and lower panels, the values of the photon indices and energies of the individual photons above 5 GeV are shown.

During most of this 2.5 year period, the source was in a high state, with a maximum observed on 10 July (MJD 57579, daily average) F(E$>$ 100 MeV) = (2.8 $\pm$ 0.3) 10^{-6} ph cm^{-2} s^{-1}. The

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

[2] https://fermi.gsfc.nasa.gov/ssc/data/analysis/user/

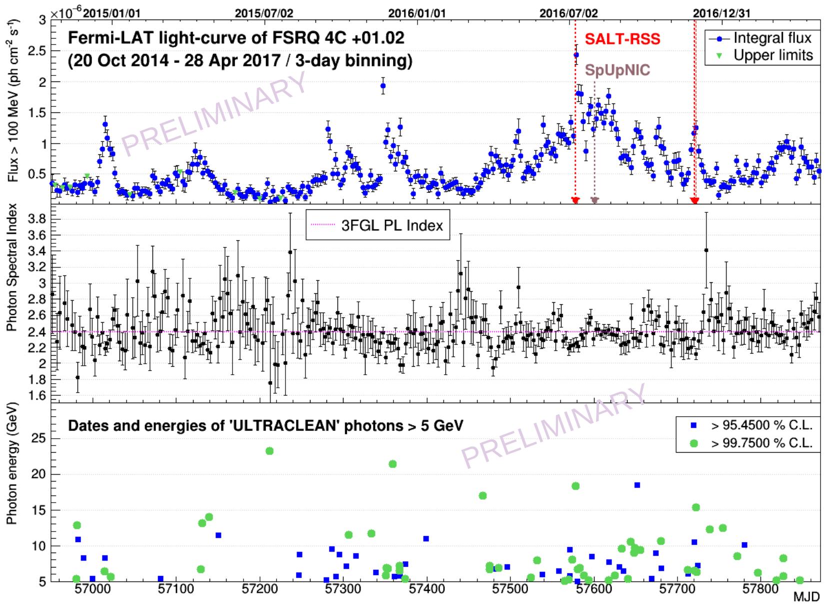

Figure 1: Upper panel: *Fermi*-LAT light-curve of 4C +01.02 above 100 MeV between 20 October 2014 and 28 April 2017 in a one-day binning. Middle panel: Optimised value of the photon index of the source. The magenta horizontal dashed-line indicates the value of the PL photon index of 3FGL. Lower panel: Arrival time and energies of high energy photons ("ULTRACLEAN" photon class, > 5 GeV). Two levels of confidences of the association of the photon with 4C +01.02 are indicated.

one-day binned *Fermi*-LAT light-curve during the 11 May–12 September 2016 period is plotted in Figure 2, along with LCO photometry data obtained in the B, V and R Johnson-Cousins filters. However, since we could not obtain a full LCO coverage during this flaring period, we can not really discuss light-curve correlations.

3. Optical spectropolarimetry with SALT-RSS

Spectropolarimetry observations were obtained with SALT-RSS in the whole optical range, using the PG 300 grating, in the "LINEAR" spectropolarimetry mode, and reduced using the `pySALT` pipeline [8] and `polsalt` package.[3] Four consecutive exposures of 600 s were triggered for each of the five observations we performed, which started on 9 July 2016 at 3:15 UT, 27 November 2016 at 19:15 UT, 28 November 2016 at 19:15 UT, 29 November 2016 at 19:36 UT and 25 July 2017 at 2:43 UT. The first four observations were obtained during flaring activity, and are labeled in Figure 1, while the fifth observation (25 July 2017) was obtained during quiescence (corresponding to a gamma-ray flux $F(E > 100\ \text{MeV}) \sim 0.1 \times 10^{-6}$ ph cm^{-2} s^{-1}). The *Swift*-XRT telescope detected 0.04 ± 0.006 counts s^{-1} in the 0.3–10 keV range[4] on 2 August 2017 (MJD 57967.91), when the gamma-ray flux was at the same level as on 25 July 2017. Count rates from *Swift*-XRT on this source ranges from ~0.03 to 0.08 counts s^{-1}.

[3]https://github.com/saltastro/polsalt

[4]http://www.swift.psu.edu/monitoring/source.php?source=PKS0106+01

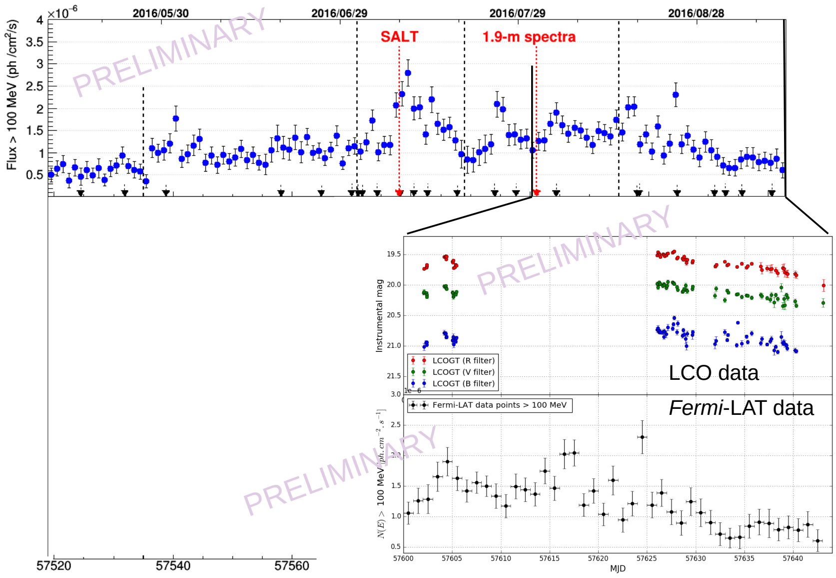

Figure 2: Upper panel: *Fermi*-LAT light-curve of 4C +01.02 above 100 MeV between 11 May and 12 September 2016, in a one-day binning. Vertical dashed arrow indicate separations between three phases of the outburst: plateau, flare and postflare. Small black arrow indicate the arrival times of high energy photons (> 5 GeV). Zoom panel: LCO data in the B, V and R Johnson-Cousins filters, compared to the *Fermi*-LAT data points from the upper panel, in the MJD 57600–57643 range.

In Figure 3, preliminary results from the five SALT-RSS observations are presented. The percentage of linear polarisation remained between 5-10% during the flare, after which it decreases to $\sim$1% when it was observed during a quiescent phase. This matches our expectation of observing a significant increase of synchrotron radiation emission from the jet, characteristic of blazar outbursts. Furthermore, a decrease of the polarisation degree is observed at the position of strong emission lines, since these originate from non-thermal emission from ther BLR.

We show in Figure 4 the normalized count spectra of the five observations. We notice a significant increase of the equivalent widths of the emission lines during quiescence. This is often observed, due to jet emission that outshines the BLR radiation field, though it has also been observed that BLR emission lines may become more luminous during flares (See [9] in the case of the FSRQ 3C 454.3).

4. Summary

We reported updates on our optical/gamma-ray observations of 4C +01.02 during its long lasting outburst in 2016, where significant flux variability was recorded, both in gamma ray and optical bands. We also compared the spectral and polarisation features observed by SALT-RSS with the observation performed on 25 July 2017 during its quiescent state. A negligeable degree of polarisation was reported at this date, compared to previous values that were observed up to $\sim$10 % during flaring activity. Broadband SED modelling is also being undertaken, considering

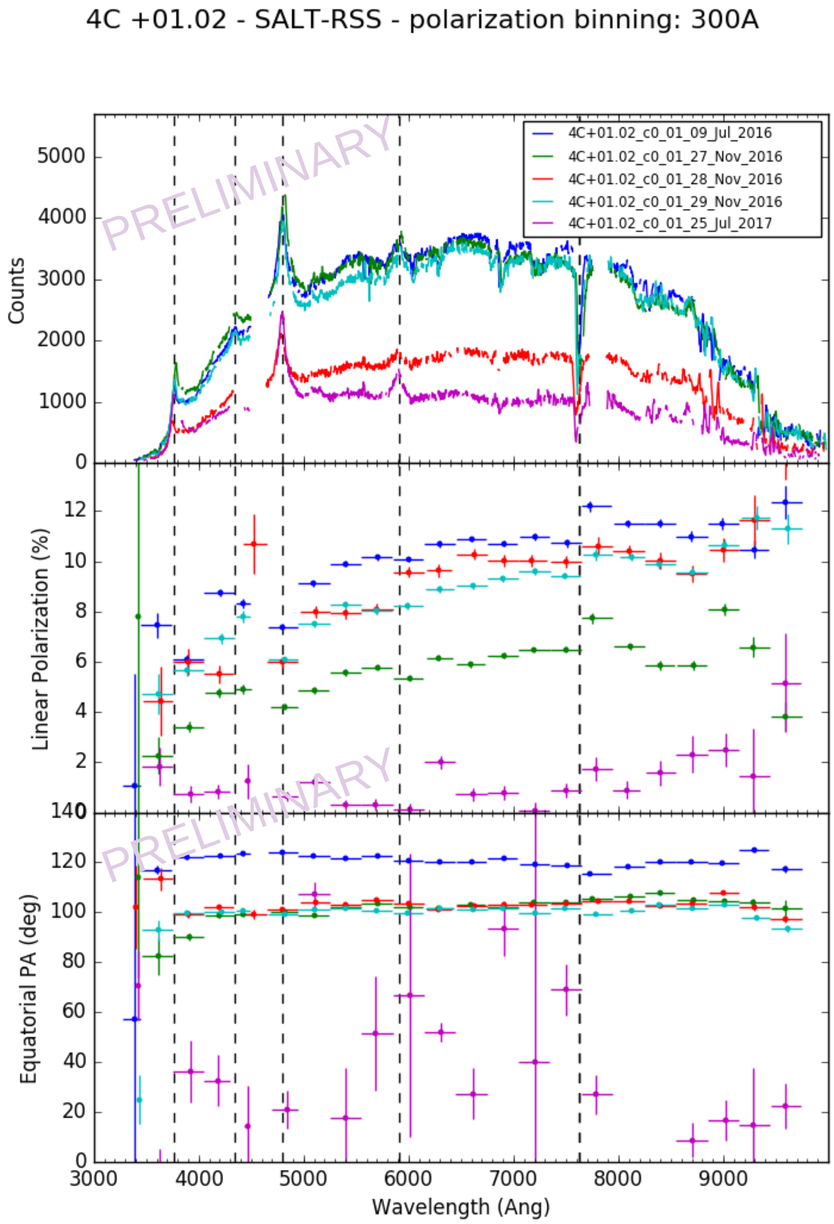

Figure 3: Preliminary SALT-RSS data reductions from 4C +01.02 data obtained on 9 July, 27, 28, 29 November 2016 and 25 July 2017 (grating PG 300 in "LINEAR" spectropolarimetry mode), combining four exposures of 600 s for each data set. Upper panel: count spectra in the ∼3500–10000 Å range. Middle panel: linear polarisation degree. Lower panel: position angle.

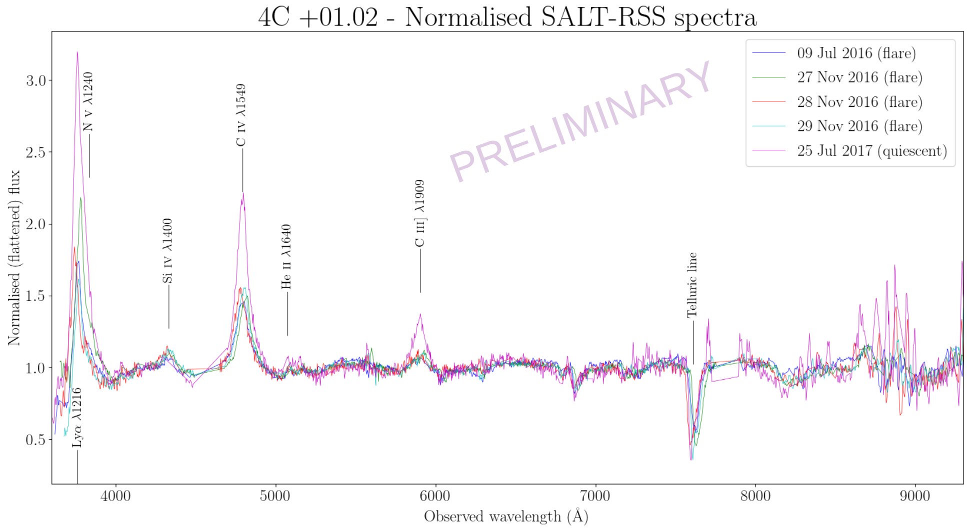

Figure 4: 4C +01.02 SALT-RSS count spectrum from Figure 3 after normalisation of the continuum to 1.

the wavelength dependence of the linear polarisation degree, providing constraints on the degree of order of the magnetic field and the mass of the supermassive black hole.

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