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MULTIWAVELENGTH STUDY OF FERMI-LAT BLAZARS VARIABILITY AND RADIATION PRODUCTION MECHANISMS

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Abstract. Quasars constitute a subclass of radio-loud active galactic nuclei that release a tremendous amount of non-thermal radiation through a pair of twin jets. When one of these jets is aligned close to the direction of the Earth, the object is then called a blazar. A consistent monitoring of these sources can help to unveil physical mechanisms at the origin of the radiation production that spreads throughout the whole electromagnetic spectrum, from radio waves to γ rays. The goal of this paper is to report some current works being undertaken in term of both spectral studies and time domain analyses of bright blazars which are observed with the *Fermi* Gamma-Ray Space Telescope and by South Africa-based optical telescopes. In particular, we present our recent and current studies on blazars 3C 454.3 and NVSS J141922-083830 respectively.

Keywords: Quasars: general – Quasars: individual: 3C 454.3 – Telescopes – Gamma rays: general – Methods: data analysis

1 Introduction

Understanding the nature of Active Galactic Nuclei (AGNs) has been a fascinating challenge of astrophysics since the middle of the 20$^{\text{th}}$ century. Though the so-called unified model of AGNs gives a comprehensive representation of Seyfert galaxies, radio galaxies, quasars, blazars, etc., we still have a lot to understand concerning the radiation production mechanisms which are the origin of the broadband spectral energy distributions (SEDs) that spread over the whole electromagnetic spectrum. In Figure 1 the unified model of AGNs is represented, consisting of a supermassive black hole (SMBH) surrounded by an accretion disk of hot plasma emitting visible and ultraviolet radiation, a relatively dense region of high-velocity gas clouds and radiation field, called the broad-line region (BLR), a pair of twin relativistic plasma jets that are probably formed by material ejected from the accretion disk, while a significant part of the matter is falling towards the SMBH in rotation in an intense magnetic fiels (Urry & Padovani 1995). In the rest of this paper we will present studies on blazars, which are the most luminous sources in the Universe, apart from γ-ray bursts. Blazars are radio-loud AGNs with one of their jets directed close to the direction of the Earth. Most of the radiation we detect from these sources is the Doppler boosted non-thermal radiation emitted within the jets. Blazars are divided into two main categories: the flat spectrum radio quasars (FSRQs) and the BL Lacs. Several recent reviews describe the current understanding as well as challenges in the AGN and blazar physics (Massaro et al. 2016; Dermer & Giebels 2016; Finke 2016).

Though it is widely accepted that the low energy component of blazar SEDs is due to the electron synchrotron emission mechanism, it is still debated whether the origin of the high energy (HE) component is produced

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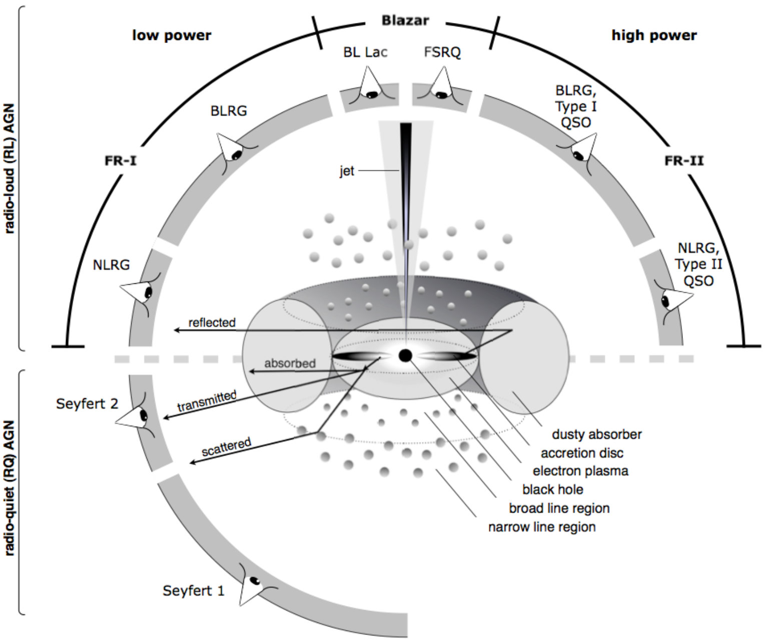

Fig. 1. The unified model of Active Galactic Nuclei (AGNs). Credit: Beckmann & Shrader (2012).

through leptonic or through hadronic processes. We presented in Britto et al. *(submitted to PoS)* a short review of some current understandings and investigations of *leptonic versus hadronic* scenarios of radiation production mechanisms in blazar jets.

The *Fermi* Gamma-Ray Space Telescope was lauched on 11 June 2008, and has observed the whole sky for the last eight years. Its main instrument, the LArge Area Telescope (LAT), is sensitive to photons between 20 MeV and >300 GeV. Most of the time the LAT is observing in survey mode, which allows us to have a scan of the whole sky every three hours (Atwood et al. 2009). This observing strategy is of particular interest for the monitoring of variable sources such as AGNs, and particularly blazars that exhibit dramatic variabilty patterns on sub-day time scales.

We present in Section 2 our previous work on searching for γ-ray absorption in the *Fermi*-LAT data of 3C 454.3, and in Section 3 our study of 3C 454.3 during its June 2014 outburst. We report in Section 4 our on-going study on blazars NVSS J141922-083830 and our projects of using optical South Africa based telescopes in complementarities to γ-ray observations.

2 Probing absorption in the BLR

Note. The results and the discussion presented in this section are taken from a previous work presented by R. J. Britto, S. Razzaque and B. Lott (Britto et al. 2015a).

FSQR 3C 454.3 is a well studied blazar, with observations spanning over many years, and particularly since it has exhibited some of the brightest blazar flares ever detected in the MeV-GeV range: in December 2009 (Striani et al. 2010; Ackermann et al. 2010), April 2010 (Ackermann et al. 2010), in November 2010 (Abdo et al. 2011, still currently the record for blazars), in June 2014 (Britto et al. 2016), and in June 2016 (Lucarelli et al. 2016; Bulgarelli et al. 2016; Ojha 2016)*. We studied the γ-ray SED of this source between 100 MeV and several tens of GeV by using Pass 8 data from the *Fermi*-Large Area Telescope (*Fermi*-LAT). It is expected that γ-ray photons in the $\sim$10-100 GeV range undergo absorption through interaction with ultraviolet photons of the BLR by electron-positron pair production ($\gamma\gamma \rightarrow e^+e^-$). If we can quantify the expected absorption for

*See also: `http://fermi.gsfc.nasa.gov/ssc/data/access/lat/msl_lc/`

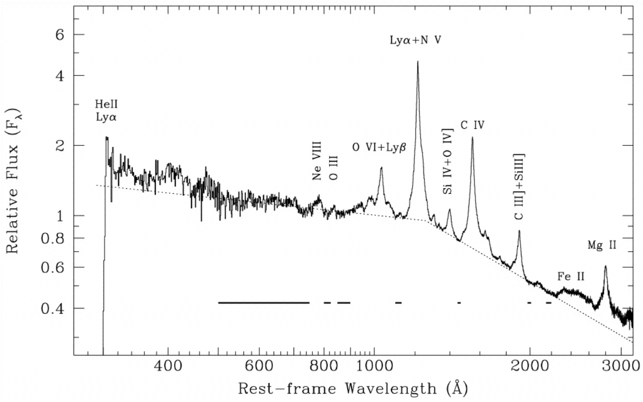

Fig. 2. Mean quasar spectrum in 1 Å bins. The dotted line represents the best-fit broken power-law continuum, excluding the region below 500 Å. The bottom lines indicate the continuum windows used in the fit. Figure 4 from Telfer et al. (2002).

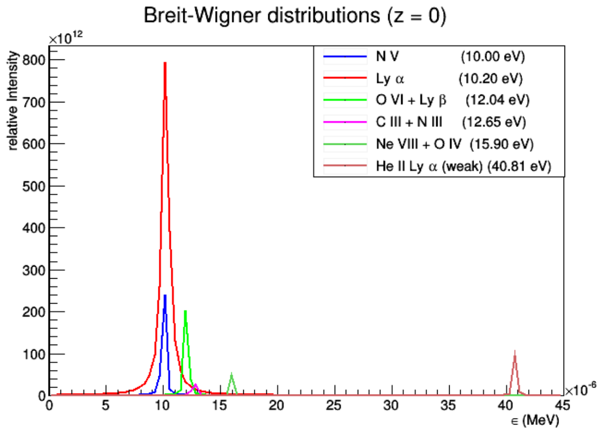

Fig. 3. Modelling of six bright ultraviolets lines of the BLR, using a Breit-Wigner distribution. Figure from Britto et al. (2015b).

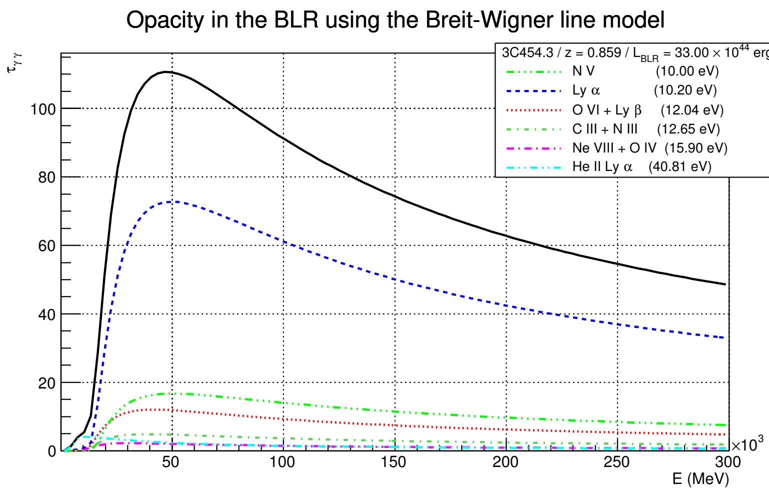

Fig. 4. Opacity $\tau_{\gamma\gamma}(E,z)$ *versus* Energy, for 3C 454.3. The opacity sum on the 6 lines is represented in plain black. Figure 1 from Britto et al. (2015a).

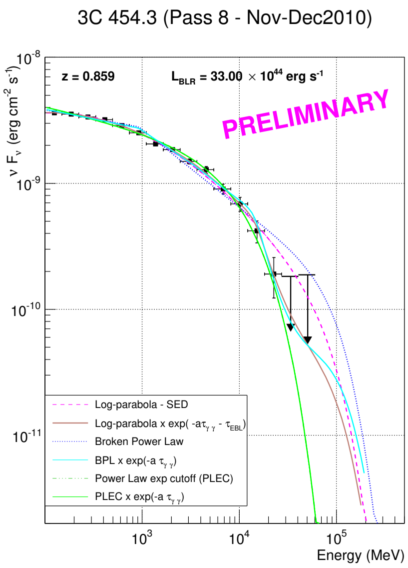

Fig. 5. SEDs of 3C 454.3 during its November-December 2010 outburst period. Figure 4 from Britto et al. (2015a).

a certain width and within a certain density of material of the BLR, it may be a precious tools to constrain the location of the γ-ray emission region: within or beyond the BLR.

We modeled the opacity of the BLR between 1 and 100 GeV, using eight prominant lines from the composite ultraviolet spectrum of radio-loud quasars compiled by Telfer et al. (2002): Nv, Lyα, Ovi, Lyβ, Ciii, Niii, Neviii and Oiv (Figure 2). We also added the Heii Lyα line in our model, under a certain assumption of its width and intensity, in order to model the $\gamma\gamma$ absorption at lower energy. These six lines correspond to an ultraviolet emission from ∼10 to 41 eV respectively. We modeled them using a *Breit-Wigner* distribution (Figure 3). In Figure 4 is shown the opacity, $\tau_{\gamma\gamma}$, of each line and the total opacity used in our model.

We fitted the *Fermi*-LAT SED of 3C 454.3 during its giant flare (02 November–05 December 2010 — MJD 55502.5-55535.5, Abdo et al. 2011) using successively the following functions: a log-parabola (LP), a broken power law (BPL), and a power law with an exponential cutoff (PLEC). To all these functions we also added

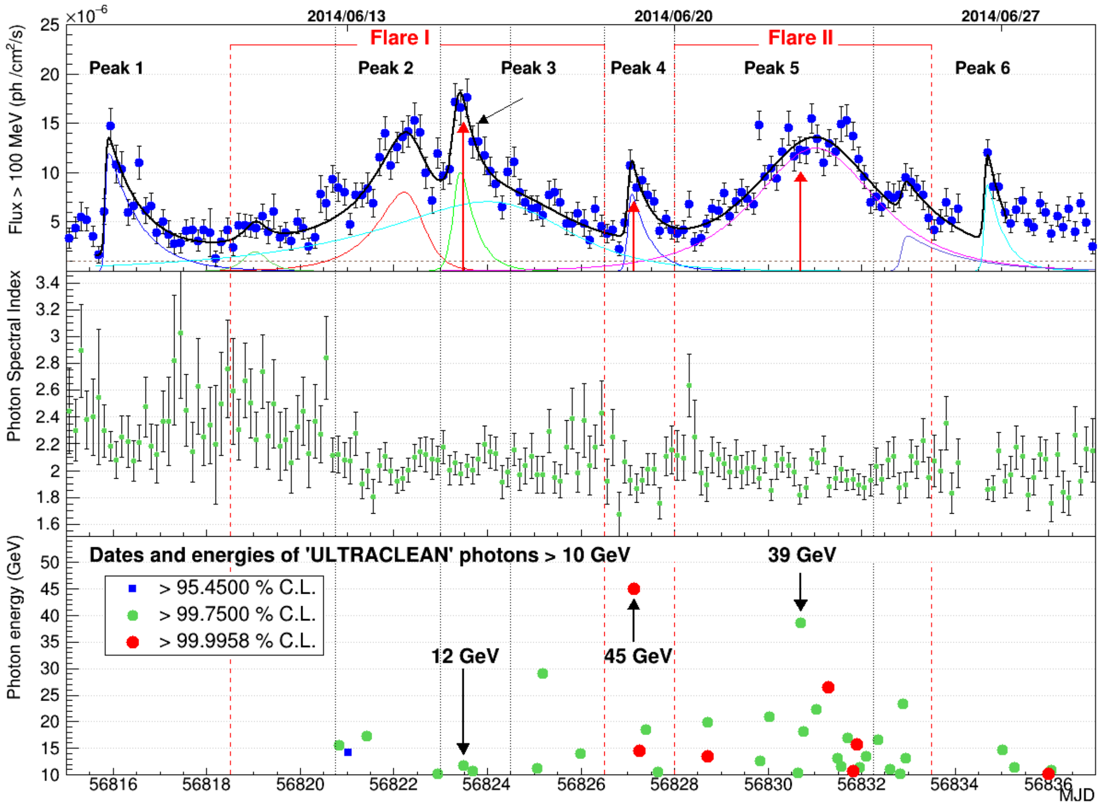

Fig. 6. *Top panel: Fermi*-LAT light-curve of the flare phase with 3-hr binning. The thin color lines correspond to the contribution of single peaks in the total fit, which is represented by the thick black line. The red arrows indicate the arrival time of the three high-energy photons used to calculate the Doppler factor, and whose energies are labeled in the bottom panel. Due to an instrumental problem, the MJD 56834.375 bin contains no data. *Middle panel:* Photon spectral index (Γ) of the PL fits of data. *Bottom panel:* Arrival time and energy of E>10 GeV photons with three different significance levels of source association (2-, 3-, and 4-σ Gaussian equivalent). Vertical red dash lines indicate the two major flaring phases (I and II), and black dotted lines indicate Peaks 2, 3, 4 and 5. Figure 2 of Britto et al. (2016).

a exponential component to model absorption by the extragalactic background light (τ_{EBL}, from the model of Finke et al. (2010)). We then compared these fits with those that do not include $\tau_{\gamma\gamma}$ (Figure 5).

The observed spectrum $F_{obs}(E)$ was given by:

$$F_{obs}(E) = e^{-\tau_{EBL}(E,z)}\ e^{-a\ \tau_{\gamma\gamma}(E,z)}\ F_{int}(E), \tag{2.1}$$

where $F_{int}(E)$ is the LP, BPL or PLEC fitting function. The parameter a is kept free in the $[10^{-5}, 1]$ range to account for the fraction of radius of the BLR in which γ rays may be absorbed.

We report a $\tau_{\gamma\gamma}$-like dip with a significance close to 3 σ in the discrepancy between $F_{obs}(E)$ and $F_{obs}(E)/e^{-\tau_{\gamma\gamma}}$, when using the BPL model only.

We found that the $\gamma\gamma$ absorption in the BLR is not significant enough to claim a discovery for the models of BLR and spectral functions we have investigated. In Britto et al. (2015a), we presented this modelling for 12 FSRQs, using 5.5 years of Pass 8 data, and also during three flaring periods. We reported hints of absorption in the case of 3C 454.3, at 3.9 σ for the 5.5 year data set, and close to 3 σ during the Nov-Dec 2010 flare (the one presented in this section). An implication of our results could be that the γ-ray emission zone in this FSRQ might be located outside or at the outer edge of the BLR (parameter $a \lesssim 0.01$). However, further investigation on binning effects on the SED fits are required. Future work is also expected to improve the modelling of the BLR. Based on another modelling of the BLR, Poutanen & Stern (2010) and Stern & Poutanen (2014) also discussed evidence of GeV γ-ray absorption in the BLR for several bright FSRQs.

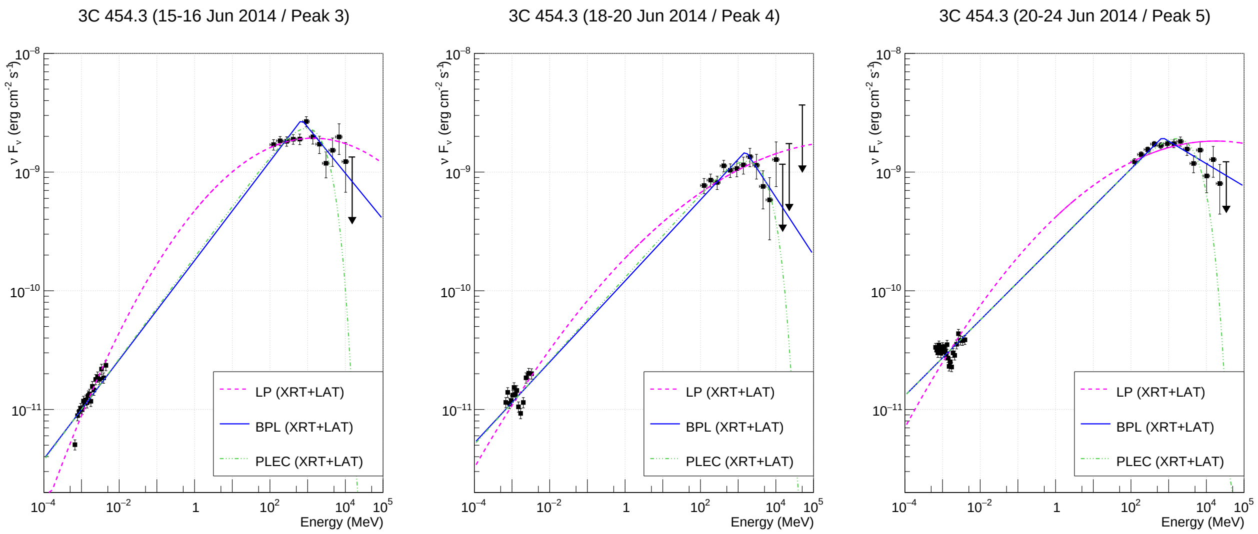

Fig. 7. SEDs of 3C 454.3 in the 1 keV-100 GeV range, with *Swift*-XRT and *Fermi*-LAT data points fitted with LP, BPL and PLEC functions, for Peak 3 (left), Peak 4 (middle) and Peak 5 (right). Figure 7 from Britto et al. (2016).

Table 1. Calculated limits of the values of δ, $\beta_{\rm jet} = \sqrt{\Gamma_{\rm jet}^2 - 1}/\Gamma_{\rm jet}$, R', $\Gamma_{\rm jet}$ and r, corresponding to the Peak 3, Peak 4 and Peak 5 subflaring events.

Subflaring events	δ	$\beta_{\rm jet}$	$\Gamma_{\rm jet}$	R' [cm]	r [cm]
Peak 3 ($T_r = 2.1$ hr)	19	0.995	10	2.3×10^{15}	2.5×10^{16}
Peak 4 ($T_r = 1200$ s)	29	0.998	16	5.6×10^{14}	1.0×10^{16}
Peak 5 ($T_r = 27.8$ hr)	14	0.991	7	2.3×10^{16}	1.8×10^{17}

3 Fast variability of FSRQ 3C 454.3 during June 2014 and constrain on the location of the γ-ray emitting region

Note. The results and the discussion presented in this section are taken from a previous work published by R. J. Britto, E. Bottacini, B. Lott, S. Razzaque and S. Buson (Britto et al. 2016).

We studied the flare of FSRQ 3C 454.3 during its May–July 2014 outburst, using the Pass 8 data representation (analysis procedure described in Britto et al. 2016). In Figure 6 is shown the light-curve of 3C 454.3 during its main flare (7–29 June 2014). We reported fast variability and the detection of HE photons above 10 GeV, mainly during the second half of the flare. Several individual flaring structures (called "Peaks") were identified.

A time-unbinned likelihood algorithm has been developed for a better estimate of the flux rise times, compared to a simple fiting of the binned light-curve (Lott et al. 2012). This allowed us to report a rise time $T_r = 1.2 \pm 0.7$ ks for Peak 4.

We calculated the opacity of the X-ray–γ-ray radiation field in the flaring blobs — associated to individual peaks — to HE photons emiting during these peaks, in order to constrain the value of the jet Doppler factor δ. We required the opacity to be equal to unity for the highest energy photon of each blob, in order to give a lower limit on δ. The X-ray–γ-ray radiation field was modelled by phenomenological fitting of the near-simultaneous *Swift*-XRT and *Fermi*-LAT data that we analysed (Figure 7). Lower limits on the jet Lorentz factor $\Gamma_{\rm jet}$, the radius of the blob R', and on its distance r from the central supermassive black hole were calculated, according the formulae $\delta = [\Gamma_{\rm jet}(1 - \beta_{\rm jet}\cos\theta)]^{-1}$, $R' \approx \delta c t_v/(1+z)$, and $r \simeq 2\Gamma_{\rm jet}^2 c t_v/(1+z)$ respectively. Our results are summarised in Table 1. Considering the radius of the canonical BLR of 3C 454.3 to be $R_{BLR} < 10^{18}$ cm (Bonnoli et al. 2011; Sbarrato et al. 2012), we get a constraint on the location of the three blobs correspondng to Peak 3, 4 and 5 to be located on the outer layers of the BLR.

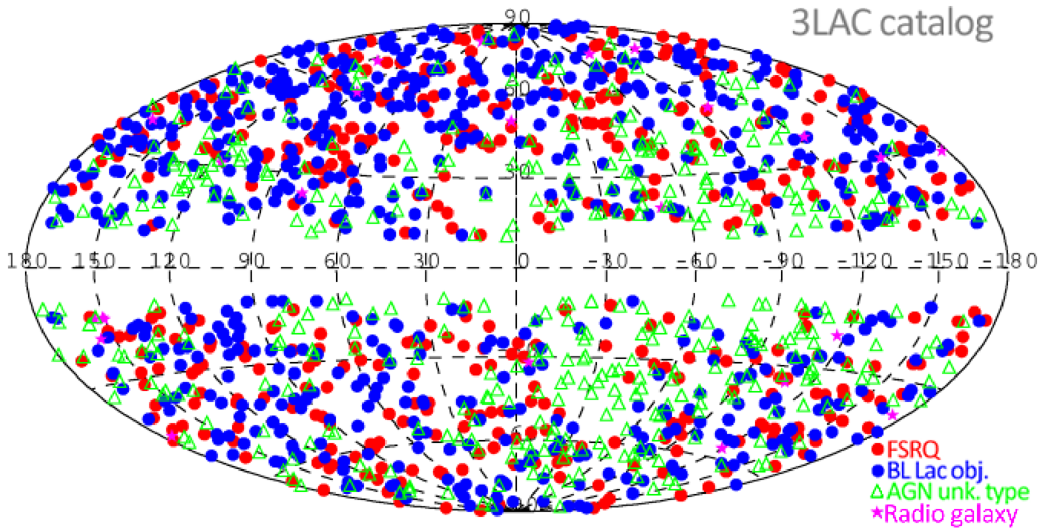

Fig. 8. Sky map of the Third *Fermi*-LAT AGN Catalog (3LAC), in Galactic coordinates. Figure 5 from Ackermann et al. (2015).

4 Observations of Fermi-LAT blazars using South Africa-based telescopes and the case of NVSS J141922-083830

The observing strategy of the *Fermi* Gamma-Ray Spece Telescope we mentioned above is of particular interest for the monitoring of variable sources such as AGNs, and particularly blazars that exhibit dramatic variabilty patterns on sub-day time scales.

The Third *Fermi*-LAT Point Source Catalog (3FGL, Acero et al. 2015), based of the analysis of the first four years of data, contains 3033 sources. The Third LAT AGN Catalog (3LAC, Ackermann et al. 2015) gives more details on the γ-ray properties of 3FGL AGNs for Galactic latitudes $|b| > 10°$. This catalogue contains 632 BL Lacs, 467 FSRQs and 460 blazar candidates of uncertain types (or BCUs), as represented in Figure 8. The vast majority of these BCU objects do not have redshift. Most of them are faint, which explains the lack of detailed optical spectra that could enable their classification.

Optical spectroscopy is used for determinating the blazar type and its redshift, whenever spectral lines can be identified. Also, in order to monitor blazar outbursts over several days, optical photometry is used to study the correlations between optical and γ-ray light-curves (see Britto 2015; Britto et al.) *(submitted to PoS)*.

The *South African Astronomical Observatory* (SAAO) was established in 1972 in the suburb of Cape Town as the merging of several South African observatories. Its offices are located on the site of the *Royal Observatory, Cape of Good Hope*, in Cape Town, but its major astronomical observations are conducted a few kilometers outside Sutherland, a small town in the Northern Cape, about 370 km North-East of Cape Town (Figures 9 and 10). It is run today by the *National Research Fondation* (NRF) of South Africa. Several telescopes operate on this site, including some that are part of collaborative effort with other countries. The biggest telescope in Africa is the *Southern African Large Telescope* (SALT), a 10-m class telescope funded by a consortium of international partners from South Africa, the United States, Germany, Poland, India, the United Kingdom and New Zealand (Buckley et al. 2006). Though SALT has been fully operational since 2011 for science observation, its upgrade is still continuing.

From all the 3LAC sources (at Galactic latitudes $|b| > 10$ deg) that are variable, belonging to the BL Lac or FSRQ or BCU classes, and that are observable by SALT in South Africa ($-75° \lesssim$ Decl $\lesssim +10°$), we have listed $\gtrsim 280$ target sources. Among this list, $\sim$50 % of them ($\sim$140) have a V mag brighter than 19. Among this rather large pool of target sources, we have undertaken the observation of several BCUs from 3LAC by using the *SpUpNIC* spectrograph of the SAAO 1.9-m telescope, Sutherland, and the *Robert Stobie Spectrograph* (RSS) of SALT, also based in Sutherland. The initial phases of this work were reported in Klindt et al. (2016b,a), and the continuing project in Van Soelen et al. *(submitted to PoS)*. We also consider the use of the *HIgh speed Photo-Polarimeter (HIPPO)* on the 1.9-m telescope.

Fig. 9. Telescope site at SAAO, Sutherland, South Africa. The 10-m class telescope SALT is visible in the backgound, in the middle of the picture. Picture from `http://www.saao.ac.za/`.

Fig. 10. Location of the major telescopes in Southern Africa: the High Energy Stereoscopy System (HESS) in Namibia; the MeerKAT radio telescope array in Karoo, South Africa — also the site of the core array of the Square Kilometer Array (SKA) radio telescope array; the Watcher robotic telescope, next to the Boyden 1.5-meter telescope, Free State, South Africa; the HartRAO radio telescope near Pretoria. Many telescopes are located at the South Africa Astronomical Observatory near Sutherland (SAAO), including the 1.9-m telescope and SALT, from which we get spectroscopy data, and MASTER-OT, etc. Credit: Google Maps, `https://maps.google.com/`.

Beside our project to perform systematic observations of BCUs during their quiescent stage for the determination of redshift and classification, we are also observing flaring blazars. An interesting example of the multiwavelength study of flaring blazars using South-Africa based telescopes is our current work on the BCU NVSS J141922-083830 (2FGL J1419.4-0835). This object is very faint in its quiescent state (magnitude V$\sim$18) and hardly detected in γ-ray in a three-day binned light-curve. On 21 February 2015, the telescope based in Kislovosk (from *Mobile Astronomical System of the TElescope-Robots–Optical Transcient* [MASTER-OT]) detected a flare of this source with a white magnitude of 14.6 (Lipunov et al. 2015). A SALT-RSS spectrum was obtained on 1 March 2015, and a redshift z=0.903 was reported, if the observed emision line is the Mg II 5325 Å, (Figure 11 and Buckley et al. 2015).

We are currently undertaking the γ-ray long term monitoring of NVSS 141922-083830 with *Fermi*-LAT, and more specifically the multiwavelength study of the source during its February-March 2015 flare (Figure 12 and Buckley et al., *(in preparation)*.

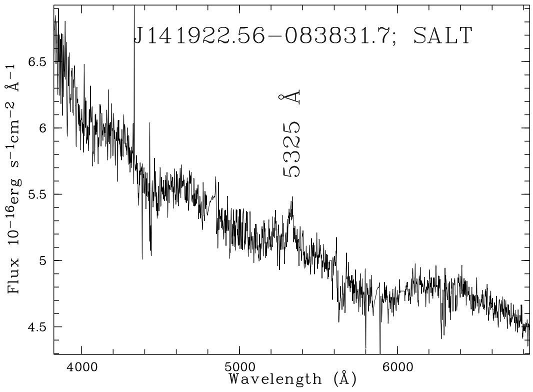

Fig. 11. SALT RSS spectrum of NVSS J141922-083830 obtained on 2015-03-01.01 UT using the PG900 lines/mm grating at an angle of 14.00 degrees, with a 1100 s exposure. The spectral window is 3780–6850 Å at a resolution of 4.8 Å with a 1.25 arcsec slit. Figure from Buckley et al. (2015).

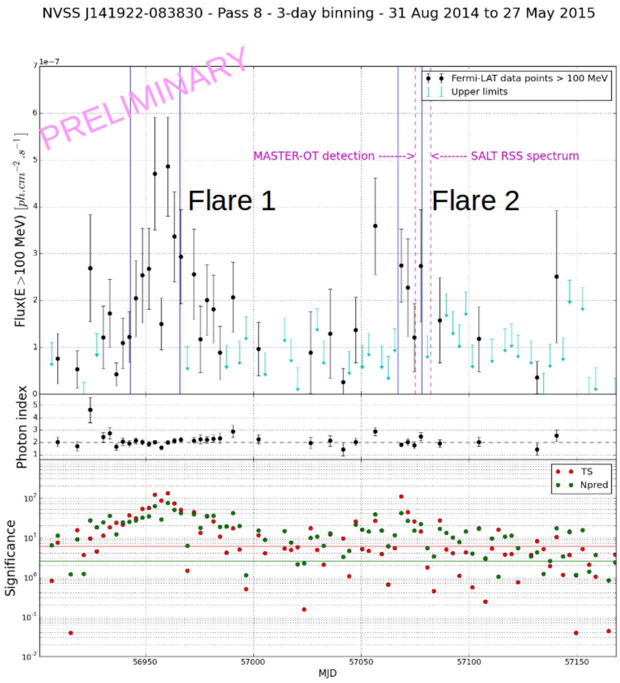

Fig. 12. Upper: *Fermi*-LAT light-curve of NVSS J141922-083830, in 3-day binning, during its two main recent outbursts (October 2014 and February–March 2015.) Dashes vertical lines indicate the date of one detection by MASTER-OT and the SALT observation. Middle: Power-law spectral index variation. Bottom: Number of photons associated to the source (predicted by the model–$N_{\rm pred}$) and significance of the detection (Test Statistics–TS). The horizontal plain lines represents the thresholds of these two quantities below which an upper limit was drawn if at least one is below its threshold.

5 Conclusions

Considering the large number of γ-ray blazars and their potential flaring outbursts, the continuous monitoring of the γ-ray sky above 20 MeV by *Fermi*-LAT, and the possibility to use South Africa based telescopes for optical photometry and spectroscopy, constitute a great potential for investigating time-domain and spectral characteristics of a large number of Southern Hemisphere sources, for which constraints on some of their physical parameters can be given.

Note added. A paper with a similar material was presented at the *MONDELLO WORKSHOP 2016. Frontier Research in Astrophysics - II (FRAPWS 2016)*. However, the conference proceeding of the Mondello conference was written to be complementary to this one. The reader may be interested to refer to Britto et al. *(submitted to PoS)*.

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