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Blue *Fermi* Flat Spectrum Radio Quasars

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ABSTRACT

Many blazars detected by the *Fermi* satellite, observed spectroscopically in the optical, are line–less, and have been classified as BL Lac objects. Optical–UV photometry of nearly one hundred of them allowed to determine the redshift for a handful of objects and redshift upper limits for the great majority. A few of these are candidates to be "blue quasars", namely flat spectrum radio quasars whose broad emission lines are hidden by an overwhelming synchrotron emission peaking in the UV. This implies that the emitting electrons have high energies. In turn, this requires relatively weak radiative cooling, a condition that can be met if the main radiative dissipation of the jet power occurs outside the broad line region. We confirm this hypothesis by studying and modelling the spectral energy distributions of the 4 "blue quasars" recently discovered. Furthermore, we discuss the distribution of *Fermi* blazars in the γ–ray spectral index – γ–ray luminosity plane, and argue that "blue quasars" objects are a minority within the blazar populations.

Key words: galaxies: active–galaxies: jets–galaxies — radiation mechanisms: non–thermal

1 INTRODUCTION

The *Fermi* satelliteis detecting γ–ray emission from a largenumber of blazars (Flat Spectrum Radio Quasars, FSRQs, and BL Lacs). From the data collected in the first two years of operation a "clean" sample was constructed from the data of the *Fermi*/Large Area Telescope (LAT) instrument, the 2LAC sample (Ackermann et al. 2011), that allows population studies.

The 2LAC sample includes 395 sources classified as "BL Lacs", 310 FSRQs, 157 sources of "unknown type", 4 Narrow Line Seyfert 1 (Abdo et al. 2009) and other 18 "non blazar" AGNs and 2 starburst galaxies. Of the 395 sources classified as BL Lacs, 56% lack a redshift determination, which limits the possibility of discussing their physical properties. When an emission lines is visible, the subdivision between the BL Lac and FSRQs categories is based on the equivalent width (EW) of the line, as measured in the rest frame: the blazar is classified as BL Lac if the rest frame EW of any permitted line is smaller than 5 Å (Stickel et al. 1991).

In order to gain redshift information for BL Lacs without any visible line, Rau et al. (2012, hereafter R12) set up a program to obtain simultaneous photometry over a wide wavelength range using the Gamma–Ray Burst Optical/Near–Infrared Detector (GROND) and the *Swift*/Optical Ultraviolet Telescope (UVOT).

80 blazars with optical/radio identification but without redshift information were selected from the 2LAC sample based on celestial position and small foreground reddening; 8 more (2 with known redshift) were included though not part of the clean 2LAC sample because of Fermi data quality problems; other 16 2LAC sources with known redshift were included for verification. In total, 104 blazars were considered: 82 have been classified as BL Lacs by Ackermann et al. (2011), 3 as FSRQs and 19 as of unknown type.

All the sources (but one, due to a lack of precise coordinates) were observed simultaneously with GROND and with the *Swift* UVOT. GROND can observe simultaneously in 7 filters, from 2.4 μm (K band) to 4000 Å (g band), while UVOT can observe in 6 filters (one filter at the time), from 5400 Å (v band) to $\sim$ 1600 Å ($uvw2$ filter; with center wavelength at 2000 Å). These data, covering the wavelength interval from 2.4 μm to 1600 Å, allow to derive photometric redshifts if the source is far enough to be affected by intervening Lyα absorption.

As a result, photometric redshifts were determined at the 90% confidence level for 11 sources, including 3 blazars that also had a previously measured spectroscopic redshift (in one case it is only a lower limit on z, derived by the presence of an intervening absorption line). Furthermore, the absence of any Lyα absorption feature in the spectrum could lead to the estimate of an *upper limit* on the redshift for 81 blazars, including 12 blazars with known spectroscopic redshift. The upper limits in these 12 sources were all consistent with the spectroscopic measurement.

Among the 11 blazars with z estimated photometrically, Padovani, Giommi & Rau (2012, P12 hereafter) discussed 4 sources, chosen because of the flat (in νF_ν) optical continuum

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(i.e. $F_\nu \propto \nu^{-\alpha}$ with $\alpha \leqslant 1$). They constructed their spectral energy distributions (SEDs), including the X–ray data of the X–Ray Telescope (XRT) onboard the *Swift* satellite and the γ–ray data of *Fermi*. They concluded that, despite their featureless optical spectrum and high synchrotron peak frequency, more typical of low power BL Lac objects (if blazars obey the "blazar sequence" as proposed by Fossati et al. 1998), these sources are probably FSRQs whose broad emission lines are swamped by the beamed non–thermal continuum.

The aim of the present paper is twofold. The first aim is to analyze in detail the SEDs of the 4 blazars discussed in P12 in order examine whether the large γ–ray luminosity together with a high frequency synchrotron peak is in contrast with the physical interpretation of the blazar sequence given in Ghisellini et al. (1998).

This interpretation assumes that the peak frequency of the blazar synchrotron emission depends mainly on the energy of the emitting electrons which, in turn, depends on the rate of radiative cooling. In this scheme, we expect that high power blazars (i.e. FSRQs) emit most of their radiation within the broad line region (BLR), which can be the dominant source of seed photons for scattering. Radiative cooling, dominated by the Inverse Compton process on this external population of seed photons (i.e. seed photons produced *externally* to the jet, so the inverse Compon process is called *external Compton,* EC for short) is severe, and therefore the energy of the relevant electrons, emitting at the peak of the spectral energy distribution (SED), is small. At the other extreme of the blazar sequence we have low power BL Lacs, that lack (or have weak) broad emission lines. EC is much less important, and the corresponding cooling is unimportant. Electrons can then reach high energies, and produce high synchrotron (and self Compton, SSC) frequencies.

However, as described in Ghisellini & Tavecchio (2008, see also Georganopoulos et al. 2001), intermediate situations may exist if the dissipative region of the jet lies *beyond* the BLR. In this case the relativistic electrons are not subject to strong EC losses, and the main emission processes become synchrotron and SSC, with some contribution from EC scattering of IR photons produced by the torus. The resulting SED is then foreseen to be similar to the SED of classical BL Lac objects. It is then possible to have a *"blue" quasar* i.e. an object with emission lines and at the same time a SSC–dominated jet. These conditions should occur in sources with a relatively small accretion disc luminosity $L_{\rm d}$ and/or a relatively large black hole mass M.

The second aim of this paper is to take advantage of the upper limits in redshift, made possible by the combination of GROND and UVOT observations, to locate these blazars in the α_γ–L_γ plane, to see if they violate the general trend observed in Ghisellini, Maraschi & Tavecchio (2009). In that paper, we analyzed only the blazars with spectroscopic redshift detected in the first 3 months of *Fermi*. We can now update the sample using the 2LAC catalog and including blazars with redshift information provided by R12.

We use a flat cosmology with $H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_{\rm M}$=0.3 and the notation $Q = 10^X Q_X$ in cgs units.

2 ANALYSIS OF *SWIFT* DATA

P12 presented the data of the 4 blazars in their sample only in the form of SED plots. Since the *Swift* data are publicly available on the *Swift* archive, we have analyzed both the XRT and UVOT data of the in order to check the results of P12.

The data were screened, cleaned and analysed with the software package HEASOFT v. 6.12, with the calibration database updated to 22 March 2012. The XRT data were processed with the standard procedure (`XRTPIPELINE v.0.12.6`). All sources were observed in photon counting (PC) mode and grade 0–12 (single to quadruple pixel) were selected. The channels with energies below 0.3 keV and above 10 keV were excluded from the fit and the spectra were rebinned in energy so to have at least 20–30 counts per bin in order to apply the χ^2 test. When there are no sufficient counts, we applied the likelihood statistic as reported by Cash (1979). Each spectrum was analysed through XSPEC v. 12.7.1 with an absorbed power law model with a fixed Galactic column density as measured by Kalberla et al. (2005). The computed errors represent the 90% confidence interval on the spectral parameters. The X–ray spectra displayed in the SED have been properly rebinned to ensure the best visualization.

UVOT (Roming et al. 2005) source counts were extracted from a circular region 5"–sized centred on the source position, while the background was extracted from an annulus with internal radius of 7" and variable outer radius depending on the nearest contaminating source. Data were integrated with the `uvotimsum` task and then analysed by using the `uvotsource` task. The observed magnitudes have been dereddened according to the formulae by Cardelli et al. (1989) and converted into fluxes by using standard formulae and zero points.

The *Swift* data analysed by us are the same used in R12 and P12. We found substantial agreement in three cases, but for the blazar RX J0035.2+1515 we found UVOT fluxes rather different from R12, and for this source we found no break. Note that in the field of RX J0035.2+1515 there is a very bright star at a distance of 36" (TYC 1187–1355–1, with B=10.39) that causes problems when subtracting the background. For its estimation, we have used an annular region of size 7"–20" centered on the blazar (see also §4.1 below).

3 BL LACS OR FLAT SPECTRUM RADIO QUASARS?

The 4 considered blazars have a featureless optical continuum, and can be classified as BL Lacs if the classical definition is adopted (i.e. an equivalent width of the lines less than 5 Å). However, P12 suggested that these blazars are instead FSRQs, whose emission lines are swamped by the relativistically boosted jet flux. The main argument for this classification is the strong radio power of these sources, that is typical of FSQRs. We agree with this interpretation, and we would like to offer another argument in favor of the FSRQ classification of these blazars.

Ghisellini et al. (2011) and Sbarrato et al. (2012), considering *Fermi* detected blazars, have shown that there is a correlation between the γ–ray luminosity and the luminosity of the broad lines, that includes not only FSRQs, but also sources that are classified as BL Lacs according to the classical subdivision (based on the EW of the lines). Furthermore, if the luminosities are measured in Eddington units, there is a divide between BL Lacs and FSRQs for $L_{\rm BLR}/L_{\rm Edd} \sim 5\times10^{-4}$ and for $L_\gamma/L_{\rm Edd} \sim 0.1$. The latter values is obtained using the isotropic equivalent of the γ–ray luminosity, i.e. the K–corrected γ–ray flux multiplied by $(4\pi d_{\rm L}^2)$, where $d_{\rm L}$ is the luminosity distance. This of course does not imply that L_γ is isotropic. If the photometric redshift of our 4 blazars is correct, then their γ–ray luminosity is large, exceeding the $L_\gamma/L_{\rm Edd} \sim 0.1$ value even for black hole masses equal to $M = 10^9 M_\odot$. An exception could be RX J0035.2+1515, if the true redshift is $z \sim 0.3$, since in this case $L_\gamma \sim 10^{45}$ erg s^{-1}, making $L_\gamma/L_{\rm Edd} < 0.1$ for $M > 8\times10^7 M_\odot$. In this case we should consider the source as a BL Lac, namely a blazar whose emission lines, if present, are intrinsically weak.

The correlation found in Sbarrato et al. (2012) concerns sources closely aligned with the line of sight, and it is foreseen that when the γ–ray sensitivity will improve, what we see now as a correlation is in fact a boundary in the $L_{\rm BLR}$–L_γ plane. Bearing this in mind, the correlation has the form

$$L_{\rm BLR} \sim 4\, L_\gamma^{0.93} \tag{1}$$

with a large scatter, since the γ–ray luminosity is highly variable in single objects even when averaging over one or two years (see e.g. Ghirlanda et al. 2011). This offers a rough way to estimate the luminosity of the broad lines. When a good optical spectrum is available, we can then suggest the minimum ratio – between the boosted non–thermal and the thermal continua – needed to hide the lines.

4 NOTES ON INDIVIDUAL SOURCES

4.1 RX J0035.2+1515

The source has been observed by the SDSS to have a featureless continuum. NED reports $z = 1.09$. On the other hand SDSS reports $z = 1.057$ as a result of an automatic analysis, and also alerts that z is actually unknown. The quoted values are not believable. Adopting the photometric redshift given in R12, $z = 1.28$, we can derive a (5σ) upper limit on the flux of the MgII line which is the most prominent broad line observable in the spectral range of SDSS. We derive $L_{\rm MgII} < 1.4\times10^{43}$ erg s^{-1}. We then use the template given in Francis et al. (1991), adding the Hα contribution (not included in Francis et al. 1991), with a relative weight of 77 (on a scale in which the Lyα is 100). The total weight of all lines is then 555 (see Celotti, Padovani & Ghisellini et al. 1997), and the weight of MgII is 34. Therefore we derive $L_{\rm BLR} = (555/34) L_{\rm MgII} < 3\times10^{44}$ erg s^{-1}. With a covering factor of 0.1, the upper limit on the accretion disc luminosity is $L_{\rm d} < 3\times10^{45}$ erg s^{-1}. The 0.1 value for the covering factor is uncertain and should be taken as an average value with some dispersion (see e.g. Baldwin & Netzer 1978; Smith 1981).

Assuming a standard, geometrically thin optically thick disc (Shakura & Sunyaev 1973), the peak frequency of its spectrum has $\nu_{\rm p} L_{\rm d}(\nu_{\rm p}) < 1.5\times10^{45}$ erg s^{-1}, a factor ~ 20 below the observed νL_ν in the optical, that has a luminosity $\sim 3\times10^{46}$ erg s^{-1}

We do not have any telling observation for the value of the black hole mass. Sbarrato et al. (2012), studying a sample of FSRQs detected by *Fermi*, calculated the average black hole mass of FSRQs: $\langle M\rangle = 5\times10^8 M_\odot$. Each black hole mass was estimated by Shen et al. (2011) through virial methods. Using this average black hole mass, the ratio $L_{\rm d}/L_{\rm Edd} < 0.05$.

As long as $L_{\rm d} \gtrsim 10^{-2} L_{\rm Edd}$, the hypothesis of a standard disc is justified (radiatively inefficient disc should corresponds to Eddington ratios smaller than 0.01).

As discussed in §3, the correlation between the BLR luminosity and the γ–ray luminosity in the *Fermi*/LAT energy band offers (Condon et al. 1998) and $\nu L_\nu \sim 2\times10^{42}$ erg s^{-1}. The source is detected in the infrared by the WISE satellite in all its four filters (3.4, 4.6, 12 and 22 μm)[1]. The corresponding data points are consistent with the extrapolation of the spectrum derived from the GROND fluxes.

We have re–analyzed the UVOT data, finding a very bright source at $\sim$ 36" from RX J0035.2+1515, as mentioned in §2. Estimating the background in a region of the sky free of sources, we have derived de–reddened fluxes significantly smaller than the ones reported in R12, and a harder spectrum, with no sign of a break. There is then the possibility that the derived photometric redshift is affected by the uncertainties caused by incorrectly subtracting the background. For this reason, we will consider for this source both the photometric redshift derived by R11, and also $z = 0.3$. This roughly corresponds to the lower limit on z due to the non–detection of the host galaxy both in the image and in its possible contribution to the SED (see Wagner et al. 1996; Sbarufatti, Falomo & Treves 2005).

4.2 SUMMS J053748–571828

Not observed by SDSS, its photometric redshift is $z = 1.55$. To estimate the presence or not of a standard accretion disc, and therefore its BL Lac or FSRQ nature, we can use the correlation between L_γ and $L_{\rm BLR}$, giving $L_{\rm BLR} \sim 6.3\times10^{43}$ erg s^{-1} and therefore an accretion disc 10 times more powerful. Please note that the dispersion around the L_γ–$L_{\rm BLR}$ is large, so the above values should be taken as an order of magnitude estimate. Nevertheless, since the optical continuum in this source has a luminosity similar to RX J0035.2+1515, it is conceivable that the synchrotron flux has swamped the (indeed present) broad emission lines, if the optical spectrum has a S/N similar to RX J0035.2+1515 (i.e. $\sim$ 40), or worse. The line of reasoning is the following: assuming that the photometric redshift is correct, we know at what frequencies the prominent broad emission line (i.e. Mg II) should appear. In order to be visible, this line should have a minimum luminosity, depending on the quality of the spectrum. Since R12 state that the optical spectrum is featureless, we can then assign a lower limit on the line luminosity assuming a S/N ratio. We find that a BLR of luminosity $\sim 6\times10^{43}$ erg is consistent with the absence of lines in the optical spectrum if the S/N <40.

The source is detected by WISE. Although not simultaneous with GROND, the IR data points lie on the extrapolation of the spectrum defined by the GROND points.

In the radio, the source flux is 99.8 mJy at 843 MHz, as reported by the Sydney University Molonglo Sky Survey (SUMSS; Mauch et al. 2003). This corresponds to $\nu L_\nu \sim 10^{43}$ erg s^{-1}, slightly larger than RX J0035.2+1515 at 1.4 GHz.

4.3 CRATES J0630–2406

Not observed by SDSS, its photometric redshift is $z = 1.6$. The L_γ–$L_{\rm BLR}$ relation gives $L_{\rm BLR} \sim 5.5\times10^{44}$ erg s^{-1}, suggesting a rather luminous disc ($L_{\rm d} \sim 5.5\times10^{45}$ erg s^{-1}, within on order of magnitude). If true, this disc luminosity would correspond to a way to estimate $L_{\rm BLR}$ and $L_{\rm d}$. Using Eq. 1 and $L_\gamma \sim 4 \times 10^{46}$ erg s^{-1}, we obtain $L_{\rm BLR} \sim 10^{44}$ erg s^{-1} (and $L_{\rm d} \sim 10^{45}$ erg s^{-1}) with an uncertainty of at least a factor 4. Reassuringly, this estimate is consistent with the value found above.

The radio information are poor, since only the 1.4 GHz NRAO VLA Sky Survey (NVSS) point is available, with a flux of 18.7 mJy

a $\nu_{\rm p} L_{\rm d}(\nu_{\rm p})$ a factor 20 below the optical flux: a spectrum of the same quality of the SDSS spectrum of RX J0035.2+1515 would not reveal any line. The source is detected by WISE. The corresponding

[1] Cutri et al. 2012; http://wise2.ipac.caltech.edu/docs/release/allsky/