High redshift Fermi blazars

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1LAC AGN Catalog (1LAC). BL Lacs and FSRQs are approximately present in equal number.

With respect to the previous sample (LAT Bright AGN Sample, hereafter LBAS), constructed after 3 months of survey (Abdo et al. 2009; hereafter A09), the number of detected blazars is about 7 times larger, as a result of the lower limiting sensitivity, obtained with the longer exposure and the smaller required significance (from 10 σ of the first 3 months to the current 4 σ level). Correspondingly, also the number of high redshift blazars detected in γ–rays increased: in the LBAS there were 5 blazars at z > 2 (and none at z > 3), while in the 1LAC catalogue there are 28 sources at z > 2 (and 2 at z > 3).

The increased number of high redshift γ–ray blazars allows us to characterize them in a meaningful way, through their Spectral Energy Distributions (SEDs) and their modelling. Indeed, the coverage at other frequencies (besides the Fermi/LAT band) includes observations by the Swift satellite for all sources both in the optical–UV band (through the Optical–UV Telescope UVOT) and the soft X–ray band (0.3–10 keV, through the X–Ray Telescope XRT).

It is also interesting to compare the properties of the high redshift blazars detected in γ–rays with the high–z blazars detected in hard X–rays by the Burst Alert Telescope (BAT) instrument onboard the Swift satellite. All blazars at z > 2 are FSRQs, so, up to now, high redshift “blazars” coincide with high redshift FSRQs, since no BL Lac objects with a measured redshift z > 2 has been detected so far. There are 10 FSRQs at z > 2 and 5 at z > 3 in the 3–year BAT all sky survey presented by Ajello et al. (2009), that have been studied in Ghisellini et al. (2010a, hereafter G10). The BAT and the LAT samples of high redshift blazars are rather well defined, since the sky coverage is quasi–uniform (excluding the Galactic plane) and we can consider these samples as flux limited.

The main aims of the present paper are then to characterize the properties of blazars detected at high energies at redshift greater than 2 and to see if we can understand the differences (if any) between the blazars detected in the two bands (γ–rays and hard X–rays). In G10, in fact, we suggested that the best way to select the

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most powerful blazars at large redshifts is through a survey in the hard X-ray band, rather than in the γ-ray one, but this was based on small numbers. None of the 10 BAT blazars at $z > 2$ is present in the LBAS catalogue, and only 4 of them are in the 1LAC sample, i.e. have been detected after 11 months of survey by the Fermi/LAT instrument. In G10 we explained this through a change of the average SED when the bolometric luminosity changes: by increasing it, the high energy hump of the SED peaks at smaller frequencies, i.e. have been detected after 11 months of survey by the Fermi/LAT instrument. In G10 we explained this through a change of the average SED when the bolometric luminosity changes: by increasing it, the high energy hump of the SED peaks at smaller frequencies, i.e. have been detected after 11 months of survey by the Fermi/LAT instrument. In G10 we explained this through a change of the average SED when the bolometric luminosity changes: by increasing it, the high energy hump of the SED peaks at smaller frequencies, i.e. have been detected after 11 months of survey by the Fermi/LAT instrument. In G10 we explained this through a change of the average SED when the bolometric luminosity changes: by increasing it, the high energy hump of the SED peaks at smaller frequencies, i.e. have been detected after 11 months of survey by the Fermi/LAT instrument.

We anticipate that our earlier suggestion remains valid, with important implications on the planned future hard X-ray survey missions, such as EXIST.

In this paper we use a cosmology with $h = \Omega_\Lambda = 0.7$ and $\Omega_M = 0.3$, and use the notation $Q = 10^X Q_\odot$ in cgs units (except for the black hole masses, measured in solar mass units).

2 THE HIGH REDSHIFT SAMPLE

We consider all blazars detected during the first year all-sky survey of Fermi and classified as “clean” in the catalogue of A10. These are all the blazars with $|b| > 10^\circ$, detected at more than the 4σ level whose identification is secure and unique. In total the ILAC clean sample contains 599 sources (A10), of which 248 are FSRQs, all with a measured redshift, and 275 BL Lacs (116 with the redshift measured). Among these, we selected the 27 blazars at $z > 2$ as listed and classified by A10, plus an additional source, Swift J1656.3–3302 (z = 2.4), that Ghirlanda et al. (2010) recently classified as FSRQ among the unidentified ILAC sources.

Five of these were already present in the LBAS list, i.e. the blazars detected at more than the 10σ level during the first 3 months of Fermi survey (A09). Four additional sources are present in the 3–years survey of Swift/BAT (A09) and they too have been studied in G10.

Table 1 lists all sources: the top 19 blazars are studied in this paper, while the bottom 9 are the sources already present either in the BAT or LBAS samples. In this paper we present the spectral energy distributions (SED) and the modelling for the “new” ones, i.e. blazars not present in our previous study (G10).

3 SWIFT OBSERVATIONS AND ANALYSIS

For all blazars studied in this paper there are Swift observations. Even when they were performed during the 11 months of the ILAC survey, they correspond to a “snapshot” of the optical–X–ray state of the source, while the γ–ray data are an average over the 11 months. Given the very rapid blazar variability, the SEDs constructed in this way should be considered, in all cases, not simultaneous (but the Swift UVOT and XRT data are indeed simultaneous).

The data were screened, cleaned and analysed with the software package HEASOFT v. 6.8, with the calibration database updated to 30 December 2009. The XRT data were processed with the standard procedures (XRTPipeline v. 0.12.4). All sources were observed in photon counting (PC) mode and grade 0–12 (single to quadruple pixel) were selected. The channels with energies below 0.2 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 $\chi^2$ test. When there are no sufficient counts, then we applied the likelihood statistic in the form reported by Cash (1979). Each spectrum was analysed through XSPEC v. 12.5.1 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. Tab. 2 reports the log of the observations and the best fit results of the X–ray data with a simple power law model. 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 a larger circular nearby source–free region. 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 from Poole et al. (2008). Tab. 3 lists the observed magnitudes in the 6 filters of UVOT.

4 MODELLING THE SED

To model the SEDs of the blazars in this sample we used the same model used in G10. It is a one–zone, leptonic model, fully discussed in Ghisellini & Tavecchio (2009). In that paper we em-
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Table 3. Summary of Swift/UVOT observed magnitudes. Lower limits are at 3σ level.

| Source   | $A_V$   | $v$     | $b$     | $u$     | $uvw1$     | $uvw2$     | $uvw3$     |
|----------|---------|---------|---------|---------|------------|------------|------------|
| 0106+01  | 0.08    | 17.98 ± 0.12 | 18.39 ± 0.07 | 17.63 ± 0.06 | 18.77 ± 0.1 | 19.75 ± 0.16 | 20.62 ± 0.22 |
| 0157–4614| 0.072   | > 20.37     | > 21.26   | 20.52 ± 0.25 | ...         | ...         | ...         |
| 0242+23  | 0.713   | ...        | ...       | ...       | > 20.66     | ...         | ...         |
| 0322+222 | 0.722   | > 18.61     | > 19.57   | > 19.29   | > 19.79     | > 20.18     | > 20.53     |
| 0420+022 | 0.719   | > 19.08     | 19.93 ± 0.34 | 19.30 ± 0.26 | 19.89 ± 0.31 | 20.13 ± 0.33 | 20.00 ± 0.21 |
| 0451–28  | 0.105   | ...        | ...       | > 20.43   | ...         | ...         | ...         |
| 0458–02  | 0.251   | 19.08 ± 0.22 | 19.51 ± 0.14 | 19.99 ± 0.26 | ...         | ...         | ...         |
| 0601–70  | 0.249   | 19.22 ± 0.22 | 19.89 ± 0.15 | 20.10 ± 0.25 | 20.55 ± 0.28 | ...         | ...         |
| 0625–5438| 0.472   | 19.31 ± 0.21 | 19.66 ± 0.18 | 18.56 ± 0.11 | 18.96 ± 0.11 | 19.89 ± 0.19 | 21.10 ± 0.33 |
| 0907+230 | 0.163   | ...        | ...       | > 20.56   | ...         | ...         | ...         |
| 1149–084 | 0.227   | ...        | > 19.16   | 18.84 ± 0.24 | 19.98 ± 0.36 | ...         | ...         |
| 1344+2744| 0.094   | 19.16 ± 0.2  | 19.63 ± 0.11 | 19.23 ± 0.11 | 19.86 ± 0.14 | 20.11 ± 0.18 | 19.88 ± 0.10 |
| 1537–2744| 0.209   | ...        | > 20.1    | > 20.47   | ...         | ...         | ...         |
| 1959–4246| 0.259   | 18.52 ± 0.07 | 19.18 ± 0.06 | 19.07 ± 0.07 | ...         | ...         | ...         |
| 2118+188 | 0.393   | > 20.08     | 20.27 ± 0.2 | 19.75 ± 0.18 | 20.52 ± 0.23 | > 21.29     | > 21.77     |
| 2135–5006| 0.078   | > 19.82     | > 20.17   | > 20.05   | ...         | ...         | ...         |

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Table 2. Summary of XRT observations. The observation date column indicates the date of a single snapshot or the years during which multiple snapshots were performed. The corresponding note reports the complete set of observations integrated. The column "Exp" indicates the effective exposure in ks, while $N_H$ is the Galactic absorption column in units of $10^{20}$ cm$^{-2}$ from Kalberla et al. (2005). $\Gamma$ is the photon index of the power law model $F(E) \propto E^{-\Gamma}$. $F_{0.2-10keV}$ is the observed (absorbed) flux. The results of the last column indicate the degrees of freedom, while the last but one column displays the reduced $\chi^2$ or the value of the likelihood (Cash 1979), in the case there were no sufficient counts to apply the $\chi^2$ test.

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$^a$ sum of observations of: 02/07/2007, 10/01/2008, 16/02/2008, 16/08/2009.

$^b$ sum of observations of: 22/03/2007, 10/04/2007, 08/08/2007, 10/08/2007, 13/01/2008, 20/04/2008, 22/04/2008, 26/10/2008, 22/04/2009.

$^c$ sum of observations of: 26/12/2008, 08/01/2009.

$^d$ sum of observations of: 21/02/2010, 25/02/2010.

$^e$ sum of observations of: 06/03/2009, 01/10/2009, 04/10/2009.

$^f$ Flux derived by using WebPIMMS with a rate of $(5 \pm 2) \times 10^{-3}$ c/s and fixed parameters.

$^g$ sum of observations of: 09/06/2006, 13/06/2006.

$^h$ sum of observations of: 08/01/2009, 13/01/2009.
phasize the relative importance of the different sources of the seed photons for the inverse Compton scattering process, and how they change as a function of the distance of the emitting region from the black hole. Here we briefly summarize the main characteristics of the model.

The source is assumed spherical (radius $R$) and located at a distance $R_{\text{diss}}$ from the central black hole. The emitting electrons are injected at a rate $Q(\gamma) \left[ \text{cm}^{-3} \text{s}^{-1} \right]$ for a finite time equal to the light crossing time $R/c$. The shape of $Q(\gamma)$ we adopt is assumed to be a smoothly broken power law with a break at $\gamma_b$:

$$Q(\gamma) = Q_0 \left( \frac{\gamma}{\gamma_b} \right)^{-s_1} + \left( \frac{\gamma}{\gamma_b} \right)^{-s_2}$$  (1)

The emitting region is moving with a velocity $\beta c$ corresponding to a bulk Lorentz factor $\Gamma$. We observe the source at the viewing angle $\theta_v$ and the Doppler factor is $\delta = 1/[\Gamma(1 - \beta \cos \theta_v)]$. The magnetic field $B$ is tangled and uniform throughout the emitting region. We take into account several sources of radiation externally to the jet: i) the broad line photons, assumed to re-emit 10% of the accretion luminosity from a shell-like distribution of clouds located at a distance $R_{\text{BLR}} = 10^{17} L_{1}^{1/2} d_{45}^{-1}$ cm; ii) the IR emission from a dusty torus, located at a distance $R_{\text{IR}} = 2.5 \times 10^{18} L_{1}^{1/2} d_{45}^{-1}$ cm; iii) the direct emission from the accretion disk, including its X-ray corona. Furthermore we take into account the starlight contribution from the inner region of the host galaxy and the cosmic background radiation, but these photon sources are unimportant in our case. All these contributions are evaluated in the blob comoving frame, where we calculate the corresponding inverse Compton radiation from all these components, and then transform into the observer frame.

We calculate the energy distribution $N(\gamma) \left[ \text{cm}^{-3} \right]$ of the emitting particles at the particular time $R/c$, when the injection process ends. Our numerical code solves the continuity equation which includes injection, radiative cooling and $e^\pm$ pair production and reprocessing. Ours is not a time dependent code: we give a “snapshot” of the predicted SED at the time $R/c$, when the particle distribution $N(\gamma)$ and consequently the produced flux are at their maximum.

For all sources in our sample, the radiative cooling time of the particles is short, shorter than $R/c$ even for low energetic particles. In Tab. 4 (last column) we have listed the values of $\gamma_c$, that is the minimum value of the random Lorentz factor of electrons cooling...
Figure 3. SED of PKS 0420+022, PKS 0451–28, PKS 0458–02 and PKS 0601–70. Symbols and lines as in Fig. 2.

Figure 4. SED of PMN 0625–5438, TXS 0907+230, TXS 0908+416 and PKS 1149–084. Symbols and lines as in Fig. 2.
in one light crossing time. Since it is always smaller than $\gamma_b$, almost all the energy injected in the form of relativistic electrons is radiated away. Most of the cooling is due to the inverse Compton scattering with broad line photons, with a minor contribution from the synchrotron and the self–Compton process. Therefore we always are in the fast cooling regime (i.e. $\gamma_c < \gamma_b$). In this regime the produced luminosity does not depend on the amount of the radiation energy density, but only on the energy content of the injected relativistic electrons.

Another implication is that, at lower energies, the $N(\gamma)$ distribution is proportional to $\gamma^{-2}$, while, above $\gamma_b$, $N(\gamma) \propto \gamma^{-(s^2+1)}$. The electrons emitting most of the observed radiation have energies
\( \gamma_{\text{peak}} \) which is close to \( \gamma_0 \), but these two energies are not exactly equal, due to the curved injected spectrum.

The accretion disk component is calculated assuming a standard optically thick geometrically thin Shakura & Sunyaev (1973) disk. The emission is locally a black body. The temperature profile of the disk is given e.g. in Frank, King & Raine (2002). Since the optical–UV emission is the sum of the accretion disk and the jet non–thermal components, for a few sources there is some degeneracy when deriving the black hole mass and the accretion rate.

We model at the same time the thermal disk (and IR torus) radiation and the non–thermal jet–emission. The link between these two components is given by the amount of radiation energy density (as seen in the comoving frame of the emitting blob) coming directly from the accretion disk or reprocessed by the BLR and the IR torus. This radiation energy density depends mainly on \( R_{\text{disk}} \), but not on the adopted accretion rate or black hole mass (they are in any case chosen to reproduce the observed thermal disk luminosity).

By estimating the physical parameters of the source we can calculate the power that the jet carries in the form of radiation (\( P_r \)), magnetic field (\( P_B \)), relativistic electrons (\( P_e \)) and cold protons (\( P_p \)) assuming one proton per electron. These powers are calculated according to:

\[
P_i = \pi R^2 \Gamma^2 c U'_i
\]

where \( U'_i \) is the energy density of the \( i\)th component in the comoving frame.

### 4.1 Intervening Lyman–\( \alpha \) absorption

Being at \( z > 2 \) the optical–UV flux of the blazars in our sample could be affected by absorption of neutral hydrogen in intervening Lyman–\( \alpha \) absorption systems. To correct for this, we use the attenuation calculated in G10 specifically for the UVOT filters, illustrated in Fig. 3 of that paper.

Full details of our calculation will be described in Haardt et al. (in preparation), together with a more refined treatment of the mean attenuation and its variance around the mean. The current procedure is very crude, especially when the attenuation is large (i.e. optical depths larger than unity) because in such cases most of the attenuation is due to very few clouds, implying a large variance. However, we note that the variance of the attenuation is largely reduced when the actual filter width is taken into account (Madau 1995). Our absorption model results in a mean number of thick systems which is \( < 1 \) for \( z \lesssim 4 \), so we do not expect excessive offset of the attenuation along individual line of sight with respect to the mean value.

When presenting the SED of our sources, we will show both the fluxes and upper limits de–reddened for the extinction due to our Galaxy and the fluxes (and upper limits) obtained by de–absorbing them with the \( \tau_{\text{eff}} \) shown in Fig. 3 in G10.

### 5 RESULTS

Table 4 lists all parameters used to model the SEDs of our blazars. Table 5 differs the different forms of power carried by the jet and Fig. 16 show the SEDs of the 19 blazars studied in this paper and the corresponding fitting model. In all figures we have marked with a grey shaded area the Fermi/LAT sensitivity, bounded on the bottom by considering one year of operation and a 5\( \sigma \) detection level, and on the top by considering 3 months and a 10\( \sigma \) detection level (this assumes a common energy spectral index of \( \alpha_\gamma \sim 1 \), the sensitivity limit for other spectral indices is slightly different, see Fig. 9 in A10). All these sources were not detected in the first 3 months, in fact the (11 months) \( \gamma \)-ray data points are very close to the lower boundary of the grey area. There are exceptions: 0106+01 (\( \sim 4 \)C+01.02) is brighter than the 3–months, 10\( \sigma \) sensitivity limits even if it has not been included in LBAS. This is due to a rather strong variability of the source, fainter in the first 3 months and brighter soon after. The same occurred for 1344–1723 and 0451–28. The opposite happened for 0227–369, 0347–211 and 0528+134 (i.e. they were brighter during the first 3 months), but their flux, averaged over 11 months, was in any case large enough to let their inclusion in the ILAC sample.

Some of the sources have a sufficiently good IR–optical–UV coverage to allow to see a peak of the SED in this band (see for instance 0420+022; 0451–28; 0458–02; 0625–5428; 0907+230; 0908+416; 1149–084; 1656–3302). The other sources have a SED consistent with a peak in this band, but the lack of data also allows for a peak at lower frequencies. We interpret the peak in the optical band as due to the accretion disk, and assume its presence also in those blazars where it is allowed, but not strictly required. By assuming a standard Shakura–Sunyaev (1973) disk we are then able to estimate both the black hole mass and the accretion rate. This important point has been discussed in G10, in Ghisellini et al. (2009) (for S5 0014+813) and in Ghisellini & Tavecchio (2009).

The radio data cannot be fitted by a simple one–zone model specialized to fit the bulk of the emission, since the latter must be emitted in a compact region, whose radio flux is self–absorbed up to hundreds of GHz. The radio emission should come from larger regions of the jet. On the other hand, when possible, we try to have some “continuity” between the non–thermal model continuum and the radio fluxes (i.e. the model, in its low frequency part, should not lie at too low or too high fluxes with respect to the radio data). In the following we briefly comment on the obtained parameters.

**Dissipation region** — The distance \( R_{\text{diss}} \) at which most of the dissipation takes place is one of the key parameters for the shape
Table 4. List of parameters used to construct the theoretical SED. Not all of them are “input parameters” for the model, because $R_{\text{BLR}}$ is uniquely determined from $L_\gamma$, and the cooling energy $\gamma_c$ is a derived parameter. Col. [1]: name; Col. [2]: redshift; Col. [3]: dissipation radius in units of $10^{15}$ cm and (in parenthesis) in units of Schwarzschild radii; Col. [4]: black hole mass in solar masses; Col. [5]: size of the BLR in units of $10^{15}$ cm; Col. [6]: power injected in the blob calculated in the comoving frame, in units of $10^{45}$ erg s$^{-1}$; Col. [7]: accretion disk luminosity in units of $10^{45}$ erg s$^{-1}$ and (in parenthesis) in units of $L_{\text{Edd}}$; Col. [8]: magnetic field in Gauss; Col. [9]: bulk Lorentz factor at $R_{\text{disk}}$; Col. [10] and [11]: break and maximum random Lorentz factors of the injected electrons; Col. [12] and [13]: slopes of the injected electron distribution $[dQ/d\gamma]$ below and above $\gamma_c$; Col. [14] values of the minimum random Lorentz factor of those electrons cooling in one light crossing time. The total X-ray corona luminosity is assumed to be in the range 10–30 per cent of the synchrotron luminosity.

of the overall SED, since it controls the amount of energy densities as seen in the comoving frame (see Ghisellini & Tavecchio 2009). For almost all sources we have $R_{\text{disk}} < R_{\text{BLR}}$, while for 0106+01, 0907+230, 1343+451, 1344–1723, 1959–4246, $R_{\text{disk}}$ is slightly larger than $R_{\text{BLR}}$, and for 0434+259 $R_{\text{disk}} \sim 2R_{\text{BLR}}$.

In all sources the dominant cooling is through inverse Compton off the seed photons of the BLR. This is true also for the few blazars in which $R_{\text{disk}} \gg R_{\text{BLR}}$ since, even if $U_{\text{BLR}}$ seen in the comoving frame is smaller, also $U_B$ is smaller, implying that the ratio $U_{\text{BLR}}/U_B$ is similar to the values in other sources [$U_{\text{BLR}}/U_B$ ranges between $30$ (1344–1723) and $\approx 100$ (0106+01, 0907+230)]. However, the decreased cooling rate in 0743+259 makes $\gamma_c$ to be larger ($\gamma_c = 102$, see Tab.4).

With larger still $R_{\text{disk}} \gg R_{\text{BLR}}$, the main seed photons for the Compton scattering process would become the photons produced by the the IR torus (if it exists), but this case does not occur for our sources.

**Compton dominance** — This is the ratio between the luminosity emitted at high frequencies and the synchrotron luminosity. The average magnetic field is found to be of the order of 1 Gauss, with a corresponding magnetic energy density that is around two orders of magnitude lower than the radiation energy density. Correspondingly, all sources are Compton dominated.

**Black hole masses** — Fig. 7 shows the distribution of black hole masses for the 28 blazars at $z > 2$ and compares them with the distribution of masses for the high redshift BAT blazars. Although the black hole masses of the BAT sample extend to larger values, there are still too few sources to estimate if the two distributions are different. It is interesting to note that all but 3 sources (0420+022, 0907+230 and 2135–5006) have black hole masses greater than $10^9 M_\odot$. In Ghisellini, Tavecchio & Ghirlanda (2009) we considered the *Fermi* blazars of $\gamma$-ray luminosity $L_\gamma > 10^{48}$ erg s$^{-1}$, finding, with the same method and model applied here, that for all these sources the black hole mass was greater than a billion solar masses. Therefore all blazars with $L_\gamma > 10^{48}$ erg s$^{-1}$ have black holes heavier than $10^9 M_\odot$, while the vast majority, but not all, blazars at $z > 2$ have such large black hole masses. We searched in the literature other estimates of the black hole masses for the objects in this sample, finding $M = 2.3 \times 10^9 M_\odot$ for 0836+710 (estimated by Liu, Jiang & Gu 2006), and other few limits for the
black hole masses for 0836+710 and 0528+134, that were however based assuming an isotropic γ-ray emission.

Disk luminosities — We are considering very powerful blazars, so we do expect large disk luminosities, not only on the basis of an expected positive trend between the observed non–thermal (albeit beamed) and the accretion luminosities, but also on the basis of the observed luminosities of the broad lines, that should linearly depend on the accretion power. What is interesting is that all the FSRQs analyzed up to now (i.e. belonging to the LBAS sample or to the subset of high redshift 1LAC and BAT samples) have a ratio $L_d/L_{Edd}$ between $10^{-2}$ and 1. This can be seen in the mid panel of Fig. 8, that shows $L_d$ as a function of the derived black hole mass. The two dashed lines correspond to the Eddington and 1% Eddington luminosities. This confirms the idea of the “blazars’ divide” as a result of the changing of the accretion mode (Ghisellini, Maraschi & Tavecchio 2009): from the standard Shakura–Sunyaev (appropriate for all FSRQs) to the ADAF–like regime (appropriate for BL Lacs). The $z > 2$ blazars analyzed here have $L_d/L_{Edd}$ ratios ranging from 0.05 and 0.7. The exact values of the disk luminosities derived here are the frequency integrated bolometric luminosities that best interpolate the data. On the other hand, any other accretion disk model has to fit the data as well, implying that our values of $L_d$ are robust, and nearly model–independent, within the limit of the uncertainties of the observed data.

Jet powers — The values listed in Tab. 5 are very similar to the values derived for other powerful Fermi FSRQs. They are not, however, the absolutely greatest powers found. This can be seen in the bottom panel of Fig. 8 showing $P_{\text{jet}}$ as a function of the black hole mass, and in the mid and bottom panels of Fig. 9 where we plot the power of the jet spent in the form of radiation ($P_r$) and the total jet power $P_{\text{jet}}$ as a function of $L_d$. We can compare the $z > 2$ 1LAC FSRQs with those present in the LBAS catalogue and the high redshift BAT blazars. Remarkably though, the $z > 2$ BAT FSRQs appear

| Name            | $\log P_r$ | $\log P_d$ | $\log P_{\text{jet}}$ | $\log P_e$ | $\log P_p$ |
|-----------------|------------|------------|-----------------------|------------|------------|
| 0106+01         | 46.19      | 45.88      | 44.71                 | 47.15      |            |
| 0157–4614       | 45.51      | 44.88      | 44.50                 | 46.71      |            |
| 0242+23         | 46.68      | 45.83      | 45.49                 | 46.96      |            |
| 0322+222        | 45.91      | 45.67      | 45.94                 | 47.36      |            |
| 0420+022        | 45.64      | 45.73      | 44.43                 | 46.68      |            |
| 0451–28         | 46.35      | 45.89      | 45.22                 | 47.53      |            |
| 0458–02         | 45.81      | 45.58      | 44.92                 | 47.32      |            |
| 0601–70         | 45.91      | 45.76      | 44.68                 | 47.00      |            |
| 0625–5438       | 45.81      | 45.63      | 44.73                 | 47.03      |            |
| 0635+0641       | 45.81      | 45.89      | 44.63                 | 47.10      |            |
| 0636+0652       | 45.61      | 45.91      | 44.68                 | 47.00      |            |
| 0640–230        | 45.86      | 44.03      | 45.30                 | 47.14      |            |
| 0645+0167       | 45.66      | 44.33      | 44.80                 | 46.96      |            |
| 1149–084        | 45.34      | 45.73      | 43.83                 | 45.24      |            |
| 1343+451        | 45.93      | 45.18      | 44.94                 | 47.17      |            |
| 1344–1723       | 45.66      | 44.74      | 44.43                 | 46.03      |            |
| 1357+2754       | 45.24      | 45.14      | 44.47                 | 46.58      |            |
| 1656.3–3302     | 46.17      | 45.44      | 45.23                 | 47.88      |            |
| 1959–4246       | 45.60      | 46.06      | 44.19                 | 46.67      |            |
| 2118+188        | 45.62      | 45.26      | 44.50                 | 46.81      |            |
| 2135–5006       | 45.63      | 45.03      | 44.68                 | 46.93      |            |

Table 5. Logarithm of the jet power in the form of radiation ($P_r$), Poynting flux ($P_d$), bulk motion of electrons ($P_e$) and protons ($P_p$, assuming one proton per emitting electron). Powers are in erg s$^{-1}$. The bottom part of the table reports the data derived in G10 and G09.
Jet powers vs accretion luminosities — Fig. 9 shows that the correlations found in G10 between $P_{\text{jet}}$ and/or $P_{\gamma}^r$ and $L_d$ are confirmed. We remind the reader that $P_{\text{jet}}$ and $L_d$ are independent quantities even if the main radiation mechanism is the inverse Compton process using broad line photons as seeds, that in turn are proportional to the accretion disk luminosity. This is because the radiative cooling of the emitting electrons is complete, implying that the produced jet luminosity becomes independent on the amount of radiation energy density. In other words: in the fast cooling regime the jet always emits all the energy of its relativistic electrons, no matter the amount of the luminosity of the accretion disk.

A least square fit returns a chance probability $P = 4 \times 10^{-8}$ that log $P_{\text{jet}}$ and log $P_{\gamma}^r$ are correlated with log $L_d$ (and the correlation are consistent with being linear). They remain significant also when considering the common redshift dependence, although the chance probability increases to $P = 4 \times 10^{-4}$ (for the $P_{\text{jet}}$--$L_d$ correlation) and to $P = 10^{-3}$ ($P_{\gamma}^r$--$L_d$).

As expected, the 1LAC blazars at high redshifts are among the most powerful, even if there are blazars at lower redshifts with comparable powers. This can be seen comparing the empty circles, corresponding to the 1LAC blazars of our sample, with the LBAS FSRQs of $L_{\gamma} > 10^{48}$ erg s$^{-1}$ (stars) and the BAT FSRQs at $z > 2$ (black diamonds). There are a few sources with $P_{\text{jet}} > L_d$, and several with $P_{\text{jet}} \sim L_d$. The jet in these blazars, only to produce the radiation we see, requires a power comparable to (or even larger than) the disk luminosity. The $P_{\text{jet}}$ power should be considered a very robust estimate of the minimum jet power: it is robust because it is almost model–independent ($P_{\text{jet}} \sim L_{\gamma}/\Gamma^2$, see G10), and it is a lower limit because it corresponds to the entire jet power being converted into radiation at the $\gamma$-ray emitting zone. Indeed, if there is one proton per emitting electron, the total jet power, dominated by the bulk motion of cold protons, becomes a factor $\sim 10$ larger than $L_d$ (bottom panel of Fig. 9, with the FSRQs of our sample distributed in a large portion of the $P_{\text{jet}}$--$L_d$ plane).

We believe that the relation between both $P_{\text{jet}}$ and $P_{\gamma}^r$ with $L_d$ is a key ingredient to understand the birth of jets: accretion must play a key role.

Comparison with other models — Several groups (Larionov et al. 2008; Marscher et al. 2008, 2010; Sikora, Moderski & Madejski 2008) proposed that the emitting region, especially during flares, is produced at distances from the central black hole of the order of 10–20 pc (much larger than what we assume) at the expected location of a reconfinement shock (e.g. Sokolov, Marscher & McHardy 2004). On the basis of an observed peculiar behaviour of the polarization angle in the optical, Marscher et al. (2008) thus suggested to lie at the extreme of the distributions, being the more powerful in $L_d$, and among the most powerful in $P_{\text{jet}}$ and $P_{\gamma}^r$. For calculating the power carried by the jet in the form of protons, we re–iterate that we have assumed one cold proton per emitting electron: if there exist a population of cold electrons, and no electron–positron pairs, than we underestimate $P_p$ and then $P_{\text{jet}}$, while if there are no cold leptons but there are pairs then we overestimate $P_p$. Finally, protons are assumed cold for simplicity (and “economy”), but they could be hot or even relativistic (if, e.g. shocks accelerate not only electrons but also protons), and in such cases the power is underestimated. For a detailed discussion about the presence of electron–positron pairs in blazars’ jets we refer to the discussions in Sikora & Madejski (2000), Celotti & Ghisellini (2008) and G10, where one can finds arguments limiting the amount of pairs in the jet. A few electrons–positrons per proton are possible, but not more.
that blobs ejected from the central region are forced by the magnetic field to follow a helical path, accounting for the observed rotation of the polarization angle in the optical. Flares (at all wavelengths) correspond to the passage of these blobs through a standing conical shock, triggered by the compression of the plasma in the shock. This has important consequences for the variability of the emission: since the emission region is located at large distances from the central engine, its size is large, and the expected variability timescale cannot be very short. Assuming $R_{\text{diss}} = 15$ pc, a jet aperture angle of $\theta_{\text{jet}} = 3^\circ$ and $\delta = 20$, we find a minimum variability time scale of $t_{\text{var}} = \theta_{\text{jet}}R_{\text{diss}}(1 + z)/(c\delta)$ of the order of 1.5 (1+z) months, that for sources at $z > 2$ implies a minimum variability timescales of 5–6 months. The main high energy emission mechanism is still the inverse Compton process, using as seeds the IR radiation of a surrounding torus (Sikora, Moderski \\ & Madejski 2008) with a possible important contribution from jet synchrotron radiation (Marscher et al. 2008, 2010). The main difficulty of these models concerns the expected variability, predicted to occur on a very long time scales, if the size of the emitting region is proportional (through e.g. the opening angle of the jet), to the distance of the source to the black hole. Instead the observed $\gamma$-ray flux in all strong $\gamma$-ray sources (the ones for which a reliable variability behaviour can be established) varies on much shorter time scales, and factor 2 flux changes can occur even on 3–6 hours (see Tavecchio et al. 2010 for 3C 454.3 and PKS 1510–089; Bondi et al. 2010; Foschini et al. 2010 and Ackermann et al. 2010 for 3C 454.3; Abdo et al. 2009b for PKS 1454–354; Abdo et al. 2010c for PKS 1502+105). This indicates that the source is compact. In turn suggests (although it does not prove) that its location cannot be too far from the black hole. It then also suggests that it is within the broad line region. In turn, this suggests that the broad lines are the main seeds for the inverse Compton scattering process. Occasionally, though, dissipation could occur further out, where the main seeds are the infrared photons produced by a putative torus surrounding the accretion disks. Since the seed photons have smaller frequencies, in these cases the produced high energy spectrum suffers less from possible effects of the decreasing (with seed frequencies) scattering Klein–Nishina cross section and less from possible photon–photon interactions leading to electron–positron pair production. The decreased importance of both effects may account for high energy spectra extending, unbroken, up to hundreds of GeV. These cases should be characterized by a longer variability timescale.

In the model of Marscher et al. (2008) a very short variability timescale implies a mini-
timescale still indicates a very compact emitting region, but nevertheless located at a large distance from the central black hole.

5.1 Comparing BAT and LAT high redshift blazars

Both the 1LAC sample and the BAT 3-years survey have a rather uniform sky coverage, and both approximate a flux limited sample. The 1LAC sample has a limiting flux sensitivity that depends on the uniform sky coverage, and both approximate a flux limited sample.

Thus the spectrum can be approximated by a broken power law. For illustration, consider the smoothly broken power law of the form

$$L(\nu) \propto \frac{(\nu/\nu_0)^{-\alpha_x}}{1 + (\nu/\nu_0)^{\alpha_y-\alpha_x}} \quad (3)$$

If the energy indices $\alpha_x < 1$ and $\alpha_y > 1$, the peak is at $\nu_{\text{peak}} = \nu_0 [(1-\alpha_x)/(\alpha_y - 1)]^{1/(\alpha_y - \alpha_x)}$. With this function we can easily calculate the ratio of the BAT [15–55 keV] to LAT [0.1–100 GeV] luminosities as a function of $\nu_{\text{peak}}$, and see if it compares well to the data.

6 SUMMARY AND DISCUSSION

The total number of $z > 2$ blazars with high energy information is 34 (28 with a LAT detection, 6 with BAT, and 4 with both). It is still a limited number, the tip of the iceberg of a much larger (and fainter) population, but it is derived from two well defined samples (LAT and BAT), that we can consider as flux limited and coming from two all sky surveys (excluding the galactic plane). The main result of studying them is that all the earlier findings concerning the physical parameters of the jet emitting zone, the jet power, and the correlation between the jet power and the disk luminosity are confirmed.

They are in agreement with the blazar sequence, i.e. their non-thermal SED are “redder” than less luminous blazar, with a large dominance of their high energy emission over the synchrotron one. This implies that the disk emission is left unhidden by the synchrotron flux, and this allows an estimate of the black hole mass and the accretion rate. The uncertainties associated with these estimates are relatively small within the assumption that the thermal component is produced by a standard Shakura–Sunyaev disk with an associated non–spinning hole. In G10 we argued that in any case the masses are not largely affected by this assumption, and in particular that in the Kerr case the derived masses are not smaller, despite the greater accretion efficiency. The possibility of an intrinsic collimation of the disk radiation appears more serious. If the disk is not geometrically thin, but e.g. a flared disk, then we expect a disk emission pattern concentrated along the normal to the disk, i.e. along the jet axis. We argued previously (Ghisellini et al. 2009) that this can be the case of S5 0014+813 at $z > 2$, the most luminous FSRQs belong to a broader (i.e. more scattered) distribution, and that the high-z BAT blazars are really the most extreme.

We can conclude that i) there is a trend between the high energy peak and the peak luminosity, ii) that this correlation has a large scatter, even if iii) the $z > 2$ FSRQs show the same trend with less scatter (but this may be due to the still small number) and finally iv) the $z > 2$ blazars in the 3-years BAT survey all lie in the highest luminosity, smallest $\nu_{\text{peak}}$ part of the plane.

When more BAT detections of high redshift LAT blazars will become available (and, conversely, when LAT will detect more BAT high–z blazars) this trend can be tested directly (i.e. without modelling the SED). The importance of this is two–fold: first we can estimate in a reasonable way the peak energy of the high energy emission having the hard X–ray and the γ–ray luminosities, and second (and more important) we could conclude that the most powerful blazars can be more easily picked up trough hard X–ray surveys, as the one foreseen with the EXIST mission (Grindlay et al. 2010).
it is very likely that at those early epochs (e.g. \(z > 2\)) all black holes are accreting close to the Eddington rate.

7 CONCLUSIONS

We summarize here our main conclusions:

- The blazars detected by Fermi at \(z > 2\) are all FSRQs, with typical “red” SEDs.
- These FSRQs are very luminous and powerful, but they are not at the very extreme of the distribution of luminosity and jet power.
- These sources have heavy black holes (\(M \sim 10^8 M_\odot\)) and accretion luminosities greater than \(\sim 10^9\) Eddington. When including all FSRQs in the LBAS sample, irrespective of redshift, the accretion disk luminosities is greater than \(1\%\) Eddington.
- The trend of redder SED when more luminous (i.e. one of the defining characteristics of the blazar sequence) is confirmed, and it is even present within the relatively small range of observed luminosity of the \(z > 2\) blazars.
- The correlation between the jet power and the disk luminosity is confirmed and points to a crucial role played by accretion in powering the jet.
- FSRQs with accretion disks closer to the Eddington luminosity have jets emitting a “redder” SED, and therefore can be more efficiently picked up by hard X-ray surveys (such as the one foreseen by EXIST), rather than by surveys in the hard \(\gamma\)-ray band.

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