The red blazar PMN J2345–1555 becomes blue

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1 INTRODUCTION

PMN J2345–1555 is a Flat Spectrum Radio Quasar (FSRQ) at z = 0.621 (Healey et al. 2008), bright in γ-rays, and detected by the Large Area Telescope (LAT) onboard the Fermi satellite in the first 3 months of its operation (Abdo et al. 2009), and later present in the 1LAC (catalog of AGN detected in the first 11 months of operations, Abdo et al. 2010) and 2LAC (first 2 years, Nolan et al. 2012). The γ-ray spectra were described by simple power laws. The fluxes above 100 MeV are reported in Tab. 1, together with the photon spectral indices. It can be seen that the source varied on long timescales, even if the reported fluxes are averaged over the entire period of observations. On the other hand the spectral index $\Gamma$ was always greater than 2, indicating a $\nu F_\nu$ peak at energies smaller than 100 MeV. This is typical for the FSRQ class (see Abdo et al. 2010; Ghisellini, Maraschi & Tavecchio 2009).

At the beginning of 2013 the source underwent a major flare, reaching, on Jan 13, 2013, a flux above 100 MeV of $2 \times 10^{-8}$ ph cm$^{-2}$ s$^{-1}$, more than 15 times the average photon flux listed in the 2LAC catalog (Tanaka 2013). Most interestingly, as noted in the telegram by Tanaka (2013), the spectral index became harder, $\Gamma = 1.78 \pm 0.13$. This implies a rising spectrum in $\nu F_\nu$, which is instead typical of low power blazars, namely high energy peaked BL Lac objects. Since the spectrum hardened, the luminosity variation between Jan 13 2013 and the average value in the 2LAC catalog was almost a factor 30. The spectral change was accompanied by a flaring behavior not only in γ-rays, but also in IR, optical and UV (Carrasco et al. 2013; Donato et al. 2013), where the source increased its flux by almost 2 orders of magnitude, and in X-rays (Donato et al. 2013), albeit with a more modest increase.

Although other FSRQs with a relatively hard γ-ray spectrum have been already detected by Fermi (discussed in Padovani, Giommi & Rau 2012 and Ghisellini et al. 2012), it is the first time that we can well document, in a given FSRQ (i.e. a blazar with relatively strong broad emission lines), the change from a soft ($\Gamma_{\text{LAT}} > 2$) to a hard ($\Gamma_{\text{LAT}} < 2$) γ-ray slope, accompanied by an intense flare of the source from the near IR to the γ-ray band. Previous hardening of the γ-ray spectrum have been observed in the FSRQ 4C +21.35 (=1222+216, Tanaka et al. 2011, interpreted by Foschini et al. 2011 as a change in the location of the dissipation region in the jet) and in BL Lac (Bloom et al. 1997).

The aim of this letter is to analyze the available data concerning the flare, to compare them to the existing older observations,

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ABSTRACT

The Flat Spectrum Radio Quasar PMN J2345–1555 is a bright γ-ray source, that recently underwent a flaring episode in the IR, UV and γ-ray bands. The flux changed quasi simultaneously at different frequencies, suggesting that it was produced by a single population of emitting particles, hence by a single and well localized region of the jet. While the overall Spectral Energy Distribution (SED) before the flare was typical of powerful blazars (namely two broad humps peaking in the far IR and below 100 MeV bands, respectively), during the flare the peaks moved to the optical–UV and to energies larger than 1 GeV, to resemble low power BL Lac objects, even if the observed bolometric luminosity increased by more than one order of magnitude. We interpret this behavior as due to a change of the location of the emission region in the jet, from within the broad line region, to just outside. The corresponding decrease of the radiation energy density as seen in the comoving frame of the jet allowed the relativistic electrons to be accelerated to higher energies, and thus produce a “bluer” SED.

Key words: BL Lacertae objects: general — quasars: general — radiation mechanisms: non–thermal — gamma-rays: theory — X-rays: general

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Table 1. Fluxes $F_{\gamma}$ in units of $10^{-8}$ ph cm$^{-2}$ s$^{-1}$ above 100 MeV and corresponding spectral indices as reported in different catalogs, and in Tanaka et al. (2013) for the Jan 13, 2013 data. The last column reports the K-corrected [0.1–100 GeV] luminosities.

| Catalog/Date | $F_{\gamma}$ [>0.1 GeV] | $\Gamma_{\text{LAT}}$ | log $L_{\gamma}$ |
|--------------|------------------------|----------------------|-----------------|
| LBAS         | 10.3 ± 1.3             | 2.42 ± 0.12          | 46.89           |
| 1LAC         | 3.5                    | 2.37 ± 0.10          | 46.44           |
| 2LAC         | 6.5                    | 2.19 ± 0.04          | 46.79           |
| Jan 13 2013  | 110 ± 20               | 1.78 ± 0.13          | 48.25           |

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and to construct a coherent picture of what caused the “red to blue” transition of this blazar. We use a cosmology with \( h = \Omega_\Lambda = 0.7 \) and \( \Omega_M = 0.3 \).

## 2 DATA ANALYSIS

### 2.1 Swift observations

*Swift* XRT and UVOT data were analyzed by using the HEASoft v. 6.13 software package with the CALDB updated on 21 January 2013. XRT data were processed with `xrtspipeline v. 0.12.6` with standard parameters. The extracted count spectra have been grouped to have at least 25 counts per bin, in order to adopt the \( \chi^2 \) test and analyzed with `xspec v. 12.8.0` in the 0.3–10 keV energy band. The basic adopted model was a redshifted power law with a fixed Galactic absorption column of \( N_{\text{H}} = 1.64 \times 10^{20} \) cm\(^{-2}\) (Kalberla et al. 2005). However, in the 2013 Jan 14 observation (obsID 00038401009) a broken power law model is required at 99.53% according to the \( \chi^2 \) test. Standard analysis steps compliant with the FSSC recommendations were then performed. Besides the target and backgrounds, all the 2FGL point sources in the field were included in the model. PMN J2345–1555 was detected with high statistical significance (TS = 340, Mattson et al. 1996) and a high flux \( F_{0.1–100\text{ GeV}} = (8.76 \pm 0.16) \times 10^{-7} \) photons cm\(^{-2}\) s\(^{-1}\) and a flat photon index \( \Gamma = -2.02 \pm 0.01 \). A significant spectral break at \( E_\text{br} = 2 \pm 0.5 \) GeV is found fitting the data with a broken power law model, with low and high spectral indices \( \Gamma_1 = 1.84 \pm 0.15 \) and \( \Gamma_2 = 2.58 \pm 0.34 \). A similar analysis, but made in logarithmically spaced energy bins, gives results consistent with this break (solid black points in Fig. 1). This suggests that the high energy hump in the SED peaks at \( \sim 2 \) GeV.

### 2.2 Fermi/LAT observations

Publicly available *Fermi* LAT data were retrieved from the Fermi Science Support Center (FSSC) and analyzed by means of the LAT Science Tools v. 9.27.1, together with the Instrument Response Function (IRF) Pass 7 and the corresponding isotropic and Galactic diffuse background models. Source (class 2) photons in the 0.1–20 GeV energy range, collected on January 11–14 and coming from direction within 10° from the nominal source position were selected and filtered through standard quality cuts. Standard analysis steps compliant with the FSSC recommendations were then performed. Besides the target and backgrounds, all the 2FGL point sources in the field were included in the model. The flux \( F_{0.2–10} \) is the unabsorbed flux in the [0.2–10 keV] band in units of \( 10^{-12} \) erg cm\(^{-2}\) s\(^{-1}\). Bottom: UVOT Observed magnitudes. *a:* Average of 2 observations on 23/12/2008 and 10/01/2009.

### Table 2

|          | 23/12/2008 | 14/01/2013 | 17/01/2013 |
|----------|------------|------------|------------|
| \( \Gamma_{\text{single}} \) | 1.6±0.4    | ...        | 1.9±0.2    |
| \( \Gamma_{\text{soft}} \)   | ...        | 2.6±0.3    | ...        |
| \( \Gamma_{\text{hard}} \)   | ...        | 1.0±0.2    | ...        |
| \( E_{\text{break}} \) (keV) | ...        | 1.7±0.4    | ...        |
| \( \chi^2/\text{dof} \)      | 0.3/1      | 3.4/6      | 2.86/8     |
| \( F_{0.2–10} \)              | 0.39±0.05  | 4.6        | 2.6        |
| \( V \)                       | 18.50±0.10 | 13.93±0.03 | 14.23±0.03 |
| \( B \)                       | 18.61±0.06 | 14.28±0.03 | 14.59±0.03 |
| \( U \)                       | 17.91±0.05 | 13.40±0.03 | 13.71±0.03 |
| \( W1 \)                      | 17.57±0.07 | 13.39±0.04 | 13.71±0.04 |
| \( M2 \)                      | 17.66±0.05 | 13.32±0.04 | 13.71±0.04 |
| \( W2 \)                      | 17.78±0.04 | 13.49±0.04 | 13.88±0.04 |

Figure 1. The SED of PMN J2345–1555 and the fitting models. Black points correspond to *Swift*/UVOT and XRT data taken on Jan 14, 2013 and to *Fermi* data integrating the flux between Jan 11 and 14. The brown points are the UVOT data taken on Jan 17, 2013. The cyan bow–tie corresponds to the average state of the first 3 months of *Fermi* operations (LBAS). Green symbols refer to archival data. We show the models for the two states, as explained in the text and with parameters listed in Table 2 with the different components labeled.
ous Swift/XRT observation the entire X-ray spectrum was flat, and could be interpreted as IC, we must conclude that the peak of the synchrotron flux shifted towards higher frequencies. As a result, also the IC bump is “bluer”, making the Fermi/LAT spectrum flat, and peaking at $\nu_{\text{IC}} \sim 2$ GeV. At the same time, the UVOT data are consistent with a synchrotron peak at $\nu_S \sim 10^{15}$ Hz.

If the IC process with seed photons of frequency $\nu_{\text{ext}}$ produced externally dominates (External Compton, EC for short), we have (see Tavecchio & Ghisellini 2008):

$$\nu_C \sim \frac{4}{3} \frac{\nu_{\text{peak}}^{\beta}}{1 + z} \rightarrow \gamma_{\text{peak}} \sim \left( \frac{3(1 + z)\nu_{\text{ext}}}{8\Gamma \nu_{\text{ext}}} \right)^{1/2}$$

where $\Gamma$ is the bulk Lorentz factor; $\delta = 1/\Gamma (1 - \beta \cos \theta_c)$; $\theta_c$ is the viewing angle and $\gamma_{\text{peak}} m_e c^2$ is the energy of the electrons emitting at the peaks of the SED. Setting $\nu_C = 4.8 \times 10^{23}$ Hz (i.e. 2 GeV) and $\Gamma = \delta$, we derive $\gamma_{\text{peak}} \sim 700 (\Gamma/15)$ or 7000($\Gamma/15$) according if $\nu_{\text{ext}}$ is the Hydrogen Ly$\alpha$ or the peak of the IR emission produced by the torus, assumed to be at $3 \times 10^{15}$ Hz. The synchrotron peak frequency $\nu_S \sim 10^{15}$ Hz then yields:

$$\nu_S = 3.6 \times 10^8 \gamma_{\text{peak}}^2 B \delta \quad \text{Hz} \rightarrow B \sim \frac{8\Gamma \nu_{\text{ext}} \nu_S}{1.1 \times 10^7 \nu_C} \quad \text{G} \quad (2)$$

This gives $B \sim 70 (\Gamma/15)$ or $0.7 \Gamma (15)$ G if the seed photons are coming from the broad line region (BLR) or from the IR torus, respectively. The very same relations hold for the SED observed when the $\gamma$-ray spectrum is steep, but with different $\nu_S$ and $\nu_C$. As we shall see, a coherent scenario explains the large shift in peak frequencies as due to the dissipative region, usually located within the BLR, moving beyond it. In such a case the reduced cooling allowed the electrons to reach larger $\gamma_{\text{peak}}$, corresponding to larger $\nu_S$ and $\nu_C$. We then apply a model along these lines.

### 3.1 The model

We use the model described in detail in Ghisellini & Tavecchio (2009), and used in our previous blazar studies. For self consistency, and to explain the main parameters listed in Tab. we repeat here the main properties of the model.

The model accounts for several contributions to the radiation energy density, and how these and the magnetic one scale with the distance $R_{\text{diss}}$ from the black hole of mass $M$. We consider radiation from the disk (i.e. Dermer & Schlickeiser 1993), the BLR (e.g. Sikora, Begelman & Rees 1994), a dusty torus (see Blazekowski et al. 2000; Sikora et al. 2002), the host galaxy light and the cosmic background radiation. It is a one–zone, leptonic model.

The emitting region is spherical, of size $R \sim 0.1 R_{\text{diss}}$. The jet accelerates in its inner parts with $\Gamma \propto R_{\text{diss}}^{1/2}$ up to a value $\Gamma_{\text{max}}$.

The electron injection function $Q(\gamma)$ [cm$^{-3}$ s$^{-1}$] is assumed to be a smoothly joining broken power–law, with a slope $\gamma Q(\gamma) \propto \gamma^{-\gamma_2}$ below and above a break energy $\gamma_2$. The total power injected into the source in relativistic electrons is $P' = m_e c^2 \int Q(\gamma) \gamma^2 d\gamma$, where $\nu_c = (4\pi/3) R^3$. The BLR, reprocessing 10% of the disk luminosity $L_d$, is assumed to be a thin spherical shell located at a distance $R_{\text{BLR}} = 10^{17} L_{d,30}^{1/2}$ cm. The radiation energy density of the broad lines is constant within the BLR, but it is seen amplified by $\Gamma^2$ by the moving blob (as long as $R_{\text{diss}} < R_{\text{BLR}}$). For illustration, Fig. shows also the case of a “ring–like” BLR, lying in the disk, shaped as a torus of radius $R_{\text{BLR}}$ and cross sectional radius equal to 0.1 $R_{\text{BLR}}$. The profile is somewhat smoother in this case. The two cases (spherical and ring–like) should bracket the possible geometrical possibilities. A dusty torus, located at a distance $R_{\text{dis}} = 2.5 \times 10^{15} L_{d,30}^{1/3}$ cm, reprocesses $\sim 30\%$ of $L_d$ in the far IR. The inner parts of the accretion disk there is an X–ray emitting corona of luminosity $L_X \sim 0.3 L_d$ with a spectrum $F(\nu) \propto \nu^{-\alpha} \exp(–\nu/150 \text{ keV})$.

The energy densities of all these external components are calculated in the jet comoving frame, and used to calculate the resulting EC spectrum. The internally produced synchrotron emission is used to calculate the synchrotron self Compton (SSC) flux.

We adopt a standard Shakura & Sunjaev (1973) accretion disk spectrum. It depends on the black hole mass $M$ and the accretion rate $\dot{M}$, that can be found if the SED shows signs of disk emission. In this case the total disk luminosity $L_d$ fixes $\dot{M}$, and the peak frequency of the disk spectrum fixes $M$. Furthermore, we are helped by the presence of broad lines, that can be used as a proxy for $L_d$. This method, detailed in Calderone et al. (2013), returns very accurate black hole masses if the peak of the disk emission is visible.

### 4 RESULTS

Fig. shows the result of the modeling: the red solid curve is the model for the data of Jan 13, 2013, and the solid blue line is the model fitting the Dec. 2008 UVOT and XRT data, together with the average $\gamma$–ray flux of the first 3 months of Fermi. Both models share the same black hole mass, accretion rate and viewing angle. All used parameters are listed in Tab. that also reports, for ease of the reader, the set of parameters used in Ghisellini et al. (2009), that considered a slightly smaller black hole mass. Fig. shows also the torus, disk and corona emission (unchanged for both states), the synchrotron component and the SSC and EC contributions for the Jan 13 SED. Particularly important is the UVOT spectrum in
from the disk (units of the BLR), the contribution of the magnetic field, and its X–ray corona, of the radiation coming directly from the disk ($U^a_d$), and its X–ray corona ($U^c_d$), of the radiation produced by the BLR ($U^b_{BLR}$) and by the torus ($U^b_t$). The two vertical grey lines mark the values $R_{\text{diss}}$ for the two states of the source. The Jan 13, 2013 flare corresponds to dissipation occurring just beyond the BLR. For illustration, we also show $U_{BLR}^c$ for a “ring–like” BLR lying in the disk, shaped as a torus of radius $R_{BLR}$ and cross sectional radius $R_{BLR}/10$.

Dec 2008, that can be interpreted as the peak of the accretion disk component. The Shaw et al. (2009) optical spectrum is visible in Fig. 2. Its flux is larger than in Dec. 2009, there is a contamination from the synchrotron component at low frequencies, an upturn at large frequencies and the broad MgII and Hβ lines are well visible. Their luminosities can be used to reconstruct the luminosity of the entire BLR (using the template of Francis et al. 1991 or Vander Berk et al. 2001) and then $L_d$. It agrees with the ones we have adopted, i.e. $L_d \approx 3.5 \times 10^{45}$ erg s$^{-1}$. Since the UVOT points show a peak in $\nu F_\nu$, we find $M = 7 \times 10^8 M_\odot$. To show how well the black hole mass can be determined, we have plotted in Fig. 2 other two disk spectra, of the same $L_d$ but with different masses (i.e. 0.4 and 1.4 billion solar masses), With these values the data are not well reproduced. By applying the virial method, Shaw et al. (2009) estimated $M \sim (3 - 6) \times 10^8 M_\odot$, using the Hβ and the MgII lines. Given the uncertainties, these values are well consistent with ours.

To reproduce the two states of the source, we have chosen to modify a minimum numbers of parameters. Besides $M$ and $M$, the models share the same magnetic field profile (i.e. the same Poynting flux $L_B \equiv R^2 \Gamma^2 B c/8$; see Tab. 4). The main changes concern the typical energies of the injected electrons, higher in the high states, the value of $R_{\text{diss}}$ and the injected power. We have furthermore assumed that in the high state the bulk Lorentz factor is somewhat larger ($\Gamma = 16$ vs. 13). As shown in Fig. 3, all these changes are consistent with the idea that the two states correspond to a different $R_{\text{diss}}$: for the “low” state, $R_{\text{diss}} < R_{BLR}$, the radiative cooling is strong, electrons cannot reach high energies and the overall SED is “red”. By moving from 600 to 1600 Schwarzschild radii, the radiation energy density drops, letting the electrons to reach higher energies. The magnetic field also decreases [$B \propto (R_{\text{diss}} \Gamma)^{-1}$], but the change of the radiation energy density is more drastic, making the Compton dominance (ratio of the inverse Compton to synchrotron luminosities) to decrease in the high state.

5 DISCUSSION

Fig. 4 shows $\gamma_{\text{peak}}$ as a function of the total radiation energy density (magnetic plus radiative) as seen in the comoving frame of the source. The random Lorentz factor $\gamma_{\text{peak}}$ corresponds to the energy of the electrons emitting most of power (both in synchrotron and in inverse Compton). The grey points are the values of blazars analyzed by us in the past (see Ghisellini et al. 2012 and references therein), while the red squares corresponds to the 4 “blue” blazars discovered by Padovani, Giommi & Rau (2012). As these authors suggested, they are very likely FSRQs with a very powerful optical synchrotron emission, that hides the emission lines. They should therefore correspond to the high state of PMN J2345–1555. The monitoring of these 4 blazars is too sparse to know if they are permanently “in the high state”, or if we caught them by

| Date       | $\log P_1$ | $\log P_{\text{ed}}$ | $\log P_e$ | $\log P_p$ |
|------------|------------|----------------------|------------|------------|
| 23/12/2008a | 44.72      | 44.56                | 43.97      | 45.92      |
| 23/12/2008  | 44.39      | 44.55                | 43.61      | 45.62      |
| 13/01/2013  | 45.53      | 44.54                | 44.67      | 45.25      |

Table 4. Jet power in the form of radiation, Poynting flux, bulk motion of emitting (therefore relativistic) electrons and cold protons, assuming one proton per emitting electron. α: set of powers derived in Ghisellini et al. (2010), where a slightly smaller black hole mass was adopted.
Figure 4. Random Lorentz factor ($\gamma_{\text{peak}}$) of the electrons emitting at the SED peaks as a function of the total energy density $U' = U'_e + U'_B$ as measured in the comoving frame. Small $\gamma_{\text{peak}}$ and large $U'$ correspond to “red” blazars, while large $\gamma_{\text{peak}}$ and small $U'$ correspond to “blue” blazars. The grey points correspond to blazar analyzed by us in the past (Ghisellini et al. 2012 and references therein), while red symbols refer to the 4 “blue” quasars studied in Padovani, Giommi & Rau (2012) and Ghisellini et al. (2012). PMN J2345–1555 is the first clear example of a blazar shifting from red to blue.

chance. In any case, PMN J2345–1555 demonstrates that a single source can indeed vary not only its overall flux by orders of magnitudes, but also its overall “look” and “color”. In our scheme this is simply due to the change of the location of the dissipation region by a factor less than 3 (from 600 to 1600 Schwarzschild radii in this case). This is sufficient to shift a blazar, in Fig. 4, from the red ($\gamma_{\text{peak}} \lesssim 10^2$ and $U' \gtrsim 0.3$ ) to the blue zone ($\gamma_{\text{peak}} \gtrsim 10^3$ and $U' \lesssim 0.3$ erg cm$^{-3}$). The top left region of the plane is populated mainly by low power, high energy peaked BL Lacs, lacking strong broad emission lines. For them, we do not expect strong variations of the cooling process when $R_{\text{diss}}$ changes (since there is no BLR). Variations are however possible due to changes in the acceleration process, in turn linked to the total power. Larger injected powers (and thus larger observed luminosities) could be associated to larger $\gamma_{\text{peak}}$, as observed in Mkn 501 (Pian et al. 1998; Tavecchio et al. 2001).

The fact that PMN J2345–1555 is the first FSRQ “caught in the act” suggests that it is a rare phenomenon. Furthermore, out of a sample of hundreds of FSRQs detected by Fermi, only 4 were found to be blue by Padovani et al. (2012). This leads us to conclude that only a few per cent of FSRQs dissipate most of their energy beyond the BLR, either occasionally or permanently. In turn, this suggests that the region where the jet dissipates the most is indeed well confined at $R_{\text{diss}} \lesssim 10^3 R_s$. Larger radii (even by a small amount), corresponding to a blue FSRQ, are rare, although not impossible.

We envisage two possibilities to have a dissipation always well localized. The first is internal shocks: two shells initially separated by $\Delta R$ and moving with different $\Gamma$ will collide at $R_{\text{diss}} \sim \Gamma^2 \Delta R$. If $\Delta R = a R_s$, and $\Gamma \sim 15$, then $R_{\text{diss}} \sim 10^3 R_s$. Larger val-

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