The $\gamma$-ray brightest days of the blazar 3C 454.3

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ABSTRACT

In the first week of 2009 December, the blazar 3C 454.3 became the brightest high-energy source in the sky. Its photon flux reached and surpassed the level of $10^{-5}$ ph cm$^{-2}$ s$^{-1}$ above 100 MeV. The Swift satellite observed the source several times during the period of high $\gamma$-ray flux, and we can construct really simultaneous spectral energy distributions (SEDs) before, during and after the luminosity peak. Our main findings are (i) the optical, X-ray and $\gamma$-ray fluxes correlate; (ii) the $\gamma$-ray flux varies quadratically (or even more) with the optical flux; (iii) a simple one-zone synchrotron inverse Compton model can account for all the considered SED; (iv) in this framework the $\gamma$-ray versus optical flux correlation can be explained if the magnetic field is slightly fainter when the overall jet luminosity is stronger and (v) the power that the jet spent to produce the peak $\gamma$-ray luminosity is of the same order, or larger, than the accretion disc luminosity.

Key words: radiation mechanisms: non-thermal – galaxies: active – galaxies: individual: 3C 454.3 – galaxies: jets.

1 INTRODUCTION

Among the flat-spectrum radio quasar (FSRQ) class of blazars, 3C 454.3 ($z = 0.859$; Jackson & Browne 1991) is one of the brightest and most variable sources. In 2005 April–May, it underwent a dramatic optical outburst, reaching its historical maximum with $R = 12.0$ (Villata et al. 2006). This exceptional event triggered observations at X-ray energies with the INTEGRAL (Pian et al. 2006) and the Swift satellites (Giommi et al. 2006). These detected the source up to 200 keV and in a brightened hard X-ray state. This strong optical and hard X-ray activity was followed by a radio outburst with about 1-yr delay (Villata et al. 2007). Despite this extraordinary activity, the lack of a $\gamma$-ray satellite at that time prevented us from concluding that this activity was due to a real increase of the jet power, since the integrated optical luminosity was of the same order of the $\gamma$-ray luminosity observed, years before, by the EGRET instrument on-board the Compton Gamma-Ray Observatory (CGRO) satellite (Nandikotkur et al. 2007). After the launch of AGILE, 3C 454.3 was seen to be very bright (Vercellone et al. 2007) and variable in the $\gamma$-ray band, being often the brightest $\gamma$-ray blazar in the sky (Vercellone et al. 2010), even if the simultaneous optical states were much fainter than during the 2005 flare. Many other active phases followed also in 2008 summer just after the launch of the Fermi satellite (Tosti et al. 2008; Abdo et al. 2009a), and in 2009 summer–fall, when the source was detected in active state all across the entire electromagnetic spectrum leading to many Astronomer’s Telegrams (ATels) (Bonning et al. 2009; Buxton et al. 2009; Gurwell 2009; Hill 2009; Striani et al. 2009a; Villata et al. 2009). This activity climaxed in 2009 December, when an extraordinary $\gamma$-ray flare occurred on December 2, seen by AGILE (Striani et al. 2009b), Fermi Large Area Telescope (LAT) (Escande & Tanaka 2009), Swift/X-ray Telescope (XRT) (Sakamoto et al. 2009) and Swift/Burst Alert Telescope (BAT) (Krimm et al. 2009).

In the case of the 2007 flare, it was possible to model its spectral energy distribution (SED) in different states with a jet whose total power was nearly constant in time (Katarzynski & Ghisellini 2007), but whose dissipation region was located at different distances $R_{\text{diss}}$ from the central power house (Ghisellini et al. 2007). In this model, the magnetic field energy density scales as $U_{B} \propto (\Gamma R_{\text{diss}})^{-2}$, where $\Gamma$ is the bulk Lorentz factor. Conversely, the radiation energy density $U_{\text{rad}}$ produced by the broad-line clouds scales as $\Gamma^{2}$ and is independent of $R_{\text{diss}}$ as long as the dissipation region is within the broad-line region (BLR). Even if the latter is most likely stratified, the contribution of the Ly$\alpha$ line to the BLR luminosity is dominant, and we identify the size of the BLR with the shell mostly emitting the Ly$\alpha$ photons. As a consequence, $U_{B}/U_{\text{rad}} \sim L_{\text{opt}}/L_{\gamma} \propto R_{\text{diss}}^{2} \Gamma^{-4}$. Even with a constant and dominating $L_{\gamma}$ and a constant $\Gamma$, we can have large variations of the optical flux by changing $R_{\text{diss}}$. These ideas were borne out in Ghisellini et al. (2007), immediately after the AGILE detection of a very bright $\gamma$-ray state accompanied by a moderate optical flux; the optical synchrotron flux can vary by a large amount even if the jet continues to carry the same power and always dissipates the same fraction of it. This assumes and implies, however, that the bulk of the electromagnetic output is in the more energetic inverse Compton component, that in this case should remain quasi-steady.

Instead, the large outburst seen in 2009 December witnessed a dramatic increase of this component. In this case, it is very likely...
that the power dissipated by the jet indeed increased, and it is likely that this is the consequence of an increase of total power carried by the jet. The luminosity reached in $\gamma$-rays exceeded $L_\gamma \sim 3 \times 10^{49}$ erg s$^{-1}$, a factor of $\sim 30$ larger than the EGRET luminosity, and also larger than the 2007 AGILE state. The goal of our present study is first to characterize the emission properties of 3C 454.3 during the 2009 November–December period, then to find the physical properties of the jet during the flare and finally to compare those with the luminosity of the accretion disc. In fact, as we shall see, the power of the jet of 3C 454.3 in the first week of 2009 December likely surpassed the luminosity of the accretion disc.

We use $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$ and $\Omega_M = 0.3, \Omega_\Lambda = 0.7$ and use the notation $Q = 10^3 Q_1$ in cgs units.

2 DATA & ANALYSIS

2.1 Data sets

This study is focused on the analysis of the multiwavelength (MWL) data gathered by the Fermi and Swift satellites in the period between 2009 November 1 and December 14. From these data we obtained day-scale resolved light curves along the whole time-span, in the $\gamma$-ray, X-ray and optical–UV band. Moreover, for some selected days we derived the spectral information needed to study the simultaneous MWL SED. These data sets are labelled according to the observation date.

In order to fully characterize the evolution of the SED across the whole dynamic range of $\gamma$-ray flux observed by Fermi, we also built a ‘low’ SED, deriving an HE spectrum of 3C 454.3 from an earlier period of observation when the source was significantly weaker in $\gamma$-rays, and matching it with Swift data from the same period.

Finally, in order to better investigate the UV portion of the SED, we matched an archival UV spectrum of 3C 454.3 observed by the Galaxy Evolution Explorer (GALEX) satellite with contemporary optical–UV data taken by Swift.

2.2 Fermi/LAT

We retrieved from the NASA data base $^1$ the publicly available data from the LAT $\gamma$-ray telescope on-board of the Fermi satellite (Atwood et al. 2009). We selected the good quality (‘DIFFUSE’ class) events observed within 10° from the source position (J2000) ($\alpha, \delta = (22^h 53^m 57.7, +16^\circ 08' 53.5')$, but excluding those observed with zenith distance of the arrival direction greater than 105°, in order to avoid contamination from the Earth albedo. We performed the analysis by means of the standard science tools, v. 9.15.2, including Galactic and isotropic extragalactic backgrounds and the P6 V3 DIFFUSE instrumental response function. For each data set (and, in case of spectra, for each energy bin), we calculated the lifetime, exposure map and diffuse response of the instrument. Then we applied to the data an unbinned likelihood algorithm (GLIKE), modelling the source spectrum with a power-law model, with the integral flux in the considered energy band and photon index left as free parameters. The minimum statistical confidence level (CL) accepted for each time (or time and energy, in the case of spectra) bin is $TS = 10$, where TS is the test statistic described in Mattox et al. (1996, see also Abdo et al. 2009b). Quoted errors are statistical, at 1$\sigma$ level. Systematic flux uncertainties are within 10 per cent at 100 MeV, 5 per cent at 500 MeV and 20 per cent at 10 GeV (Rando 2009).

$^1$http://fermi.gsfc.nasa.gov/
Table 1. Results of the γ-ray analysis on *Fermi*-LAT data; only the data sets used for the MWL SED are reported. For each data set, the effective source on-time $t_{\text{on}}$, the photon indices $\Gamma_1$ and $\Gamma_2$, the break energy $E_{\text{break}}$, the integral flux in the 0.1–100 GeV band $F_{\nu,0.1-100\text{GeV}}$ and the TS value of the unbinned likelihood analysis are reported. Uncertainties are statistical only, at 1σ level; systematics on flux measurement are within 10 per cent at 100 MeV, within 5 per cent at 500 MeV and within 20 per cent at 10 GeV. For the 06/11/09 data set, the relative weakness of the flux makes perfectly adequate a simple power-law model which is also reported for reference.

| Obs. date | $t_{\text{on}}$ (ks) | $\Gamma_1$ | $\Gamma_2$ | $E_{\text{break}}$ (GeV) | $F_{\nu,0.1-100\text{GeV}}$ ($10^{-6}$ ph cm$^{-2}$ s$^{-1}$) | TS |
|-----------|-----------------|------------|------------|----------------|----------------|----|
| Low       | $5.9 \times 10^3$ | $2.33 \pm 0.03$ | $3.37 \pm 0.27$ | $2.00 \pm 0.38$ | $0.61 \pm 0.02$ | 4687 |
| 06/11/09  | 61              | $2.66 \pm 0.21$ | $3.80 \pm 1.20$ | $1.10 \pm 0.57$ | $2.10 \pm 0.30$ | 218 |
| 27/11/09  | 37              | $2.13 \pm 0.09$ | $3.17 \pm 0.54$ | $1.94 \pm 0.56$ | $7.58 \pm 0.86$ | 500 |
| 01/12/09  | 44              | $2.33 \pm 0.11$ | $3.15 \pm 0.38$ | $0.97 \pm 0.34$ | $10.76 \pm 0.87$ | 1100 |
| 02/12/09  | 39              | $2.37 \pm 0.06$ | $3.17 \pm 0.46$ | $2.70 \pm 0.26$ | $21.6 \pm 1.2$ | 2497 |
| 03/12/09  | 40              | $2.28 \pm 0.06$ | $3.42 \pm 0.87$ | $5.86 \pm 0.36$ | $15.94 \pm 0.98$ | 1915 |

Table 2. Synopsis of the results of the X-ray analysis performed on *Swift*/XRT data. Only the data sets used for modelling the MWL SED of 3C 454.3 are reported. For each one of these, the exposure time $t_{\text{exp}}$, the photon indices $\Gamma_1$ and $\Gamma_2$, the break energy $E_{\text{break}}$, the normalization factor of the differential spectrum at 1 keV $f_0$, the observed (not de-absorbed) flux in the 0.2–10 keV band $F_{\nu,0.2-10\text{keV}}$, the intrinsic luminosity in the same band $L_{\nu,0.2-10\text{keV}}$ and the goodness-of-fit statistic $\chi^2$ (reduced $\chi^2$) with the corresponding number of degrees of freedom (d.o.f.) are reported. The 'low' data set results from the addition of observations made between 2008 December 25 and 2009 January 01 (ObsID from 00090023002 up to 00090023008) while the other data sets come from single pointings and are labelled with the date of observation. Spectra have been dereddened according to the $N_H = 6.6 \times 10^{20}$ cm$^{-2}$ value derived from Raiteri et al. (2008). The errors on the observed fluxes are within the 10 per cent level (at 90 per cent CL).

| Obs. date | $t_{\text{exp}}$ (ks) | $\Gamma_1$ | $\Gamma_2$ | $E_{\text{break}}$ (keV) | $f_0$ ($10^{-2}$ ph cm$^{-2}$ s$^{-1}$ keV$^{-1}$) | $F_{\nu,0.2-10\text{keV}}$ ($10^{-11}$ erg cm$^{-2}$ s$^{-1}$) | $L_{\nu,0.2-10\text{keV}}$ ($10^{47}$ erg s$^{-1}$) | $\chi^2$ (d.o.f.) |
|-----------|-----------------|------------|------------|----------------|----------------|----------------|----------------|---------|
| Low       | See caption     | 9.0        | 1.13±0.30  | 1.13±0.30 | 1.40±0.36 | 0.15±0.01 | 1.1 | 0.34 | 0.89 (43) |
| 06/11/09  | 00035050070     | 1.0        | 1.52±0.07  |          |          | 2.2±0.2 | 6.6 | 2.1 | 0.96 (38) |
| 27/11/09  | 00035050073     | 0.9        | 1.42±0.06  |          |          | 3.0±0.2 | 11.0 | 3.1 | 1.13 (53) |
| 01/12/09  | 00035050074     | 1.1        | 1.43±0.04  |          |          | 4.5±0.3 | 16.0 | 4.5 | 1.08 (87) |
| 02/12/09  | 00035050075     | 1.2        | 0.98±0.19  | 1.56±0.07 | 1.2±0.2 | 2.2±0.2 | 17.0 | 4.8 | 0.98 (103) |
| 03/12/09  | 00035050076     | 1.0        | 1.43±0.04  |          |          | 5.2±0.3 | 18.0 | 5.2 | 0.88 (89) |

observations. The derived HE spectrum allowed to explore the whole available dynamic range of 3C 454.3 γ-ray emission. For each data set, we split the LAT observed band in logarithmically spaced energy bins, and applied in each the unbinned likelihood algorithm. In addition to the request that TS > 10, we further requested that the model predicted at least five photons from the source; when needed, we merge in a single, wider bin the HE bins that did not fulfil this last request. These quality criteria are similar (and somehow more restrictive) to those adopted by Abdo et al. (2010b). For each spectrum, we cross-checked this analysis performed in bins of energy with an unbinned analysis on the whole 0.1–100 GeV band, where we modelled the source with a broken power-law model, in agreement with Abdo et al. (2010b). The results of the two methods were consistent within errors, even if the analysis in bins of energy, that does not exploit the full information of the event distribution across the whole LAT bandpass, leads to wider error bars. We report in Table 1 the parameters of the model, while the SED points are plotted in Fig. 4.

2.3 Swift

We analysed the data from observations performed between 2009 November 1 and December 14. We also analysed data from late 2008 December, contemporary to the lowest γ-ray state of 3C 454.3 seen by *Fermi*. Finally, UVOT data from a pointing in 2008 October were analysed, as we wanted to compare this observation with a roughly simultaneous *GALEX* archival UV spectrum of the source (see Section 3.2).

The data from the two narrow-field instruments on-board *Swift* (Gehrels et al. 2004) have been processed and analysed with *heasoft* v. 6.8 and with the CALDB updated on 2009 December 30.

2.3.1 X-Ray Telescope

Data from the XRT (0.2–10 keV; Burrows et al. 2005) were analysed using the *xrtpipeline* task, set for the photon counting or window timing modes and having selected single pixel events (grade 0). In the case of the light curve, we converted the observed counts rates to fluxes assuming a common $\Gamma = -1.6$ photon index and with absorption fixed at the Galactic value $N_H^{\text{Gal}} = 6.6 \times 10^{20}$ cm$^{-2}$ derived from $A_B = 0.46$ (Raiteri et al. 2008). The resulting light curve is shown in the middle panel of Fig. 1.

We extracted the spectra in order to build SED simultaneous to *Fermi/LAT* by using default regions. Data were rebinned in order to have at least 30 counts per energy bin. Power-law models have been fitted to the spectra, except for two cases, the 'low' state and the spectrum from December 2, when a broken power-law model fitted the data significantly better (ftest > 99 per cent). In Table 2 we report the spectral parameters for the observations used for modelling the SED.
2.3.2 Ultraviolet–Optical Telescope

Data from the UV telescope UVOT (Roming et al. 2005) were analysed by means of the uvtimsum and uvsourcetasks with a source region of 5 arcsec, while the background was extracted from a source-free circular region with radius equal to 50 arcsec (it was not possible to use an annular region, because of a nearby source). A total of 19 UVOT observations have been performed and analysed between November 1 and December 14. The extracted fluxes are plotted in the lower panel of Fig. 1. The Galactic extinction has been corrected assuming $A_B = 0.46$ and $R_V = A_V/E(B-V) = 3.1$ (according to Raiteri et al. 2008), and the extinction law of Cardelli, Clayton & Mathis (1989). The observed magnitudes from the five pointings used for the MWL SED are reported in Table 3; uncertainties include systematics. The observation made on 2008 October 1, roughly contemporary to the GALEX archival spectrum (see Section 2.4), is also reported in the table. The UVOT data set used for the modelling of the ‘low’ state is built with pointings made between October 25 and 2009 January 1. In this case the reported magnitudes are the mean values over the observations, while the uncertainties are calculated as $\sigma = \sqrt{\sigma_{\text{stat}}^2 + \sigma_{\text{sys}}^2}$, where $\sigma_{\text{stat}}$ is the mean statistical uncertainty on the single observation and $\sigma_{\text{sys}}$ is the sample standard deviation of the magnitude distribution, and keeps into account the variability of the source.

2.3.3 Burst Alert Telescope

Swift monitors the sky in the hard X-ray band by means of the BAT, a coded mask telescope sensitive in the 15–150 keV band (Barthelmy et al. 2005). We retrieved from the HEASARC hard X-ray transient monitor data base the daily sampled light curve of 3C 454.3 in the 15–50 keV band, and converted the count rates to fluxes assuming that the BAT monitors the sky in the hard X-ray band by means of the BAT, a satellite, in flight since 2003 April 28 and performing an all-sky survey in the 15–50 keV band (Barthelmy et al. 2005).

2.4 GALEX

The Galaxy Evolution Explorer (Martin et al. 2005) is a NASA satellite, in flight since 2003 April 28 and performing an all-sky survey in the far-UV (FUV, $\sim$154 nm) and near-UV (NUV, $\sim$232 nm) with resolution $R \equiv \lambda/\Delta\lambda \sim 200$ in NUV slit-less spectroscopy (Morrissey et al. 2007). We retrieved from the MAST³ data base a publicly available spectrum of 3C 454.3, obtained from ³Multi-mission Archive at the Space Telescope Science Institute, http://galex.stsci.edu/GR4/

2 http://heasarc.gsfc.nasa.gov/docs/swift/results/transients/

Table 3. Summary of Swift/UVOT observed magnitudes. Only the data sets that we used for modelling the MWL SED of 3C 454.3 are reported here, out of the total of 19. In addition, we report the UVOT observation that we compared to the GALEX archival spectrum in Fig. 3. The data set used for the ‘low’ state includes seven UVOT pointings, with obsID starting from 000090023002 up to 000090023008. Magnitudes are not dereddened; errors include systematics.

| Obs. date       | ObsID       | $v$  | $b$   | $u$  | $uvw1$ | $uvw2$ | $uvw3$ |
|-----------------|-------------|------|-------|------|--------|--------|--------|
| 01/10/08 (GALEX)| 00031216062 | 15.42| 15.92 | 15.24| 15.41  | 15.50  | 15.71  |
| Low             | See caption | 16.23| 16.72 | 15.93| 15.96  | 15.92  | 16.18  |
| 06/11/09        | 00035050070 | 15.88| 16.33 | 15.60| 15.68  | 15.68  | 15.86  |
| 27/11/09        | 00035050073 | 14.77| 15.25 | 14.58| 14.85  | 14.95  | 15.13  |
| 01/12/09        | 00035050074 | 14.67| 15.20 | 14.57| 14.79  | 14.93  | 15.16  |
| 02/12/09        | 00035050075 | 14.49| 15.02 | 14.25| 14.56  | 14.67  | 14.89  |
| 03/12/09        | 00035050076 | –    | –     | –    | –      | –      | –      |

Figure 2. Correlation between the non-thermal UV flux (UVOT filter $uvw2$, subtracting the disc and the Ly$\alpha$ contributions), non-thermal optical flux (UVOT filter $b$, subtracting the disc contribution), non-thermal X-rays and the $\gamma$-ray flux. The grey vertical stripe indicates the contribution of the accretion disc plus the tail of the Ly$\alpha$ line entering in the $uvw2$ frequency range. The dashed lines are the linear fit to the $\gamma$-ray flux with the $uvw2$ and X-ray fluxes (see text).

three exposures taken between 2008 September 30 and October 2. This spectrum is plotted in Fig. 3, and its relevance is discussed in Section 3.2.

3 OPTICAL AND X-RAY VERSUS $\gamma$-RAY FLUX

Fig. 2 shows the $\gamma$-ray flux as a function of the flux in the UVOT $uvw2$ and $b$ filters and as a function of the XRT X-ray flux. From the $uvw2$ flux we have subtracted the contribution of the accretion disc (0.55 mJy) and the tail of the Ly$\alpha$ line (contributing for 0.094 mJy) intercepted by this filter (see Fig. 3). For the $b$ fluxes, we have subtracted a disc contribution of 0.64 mJy.

The total time interval is the same shown in Fig. 1, i.e. about 1.5 months. The $\gamma$-ray flux correlates with both the UV–optical and X-ray fluxes, and the correlation is more than linear: for a total variation of a factor of $\sim20$ of $F_{\gamma}$, the optical–UV and the X-ray variability amplitude is a factor of $\sim3–4$. The vertical grey stripe indicates the flux contribution in the $uvw2$ UVOT filter due to the accretion disc emission according to our model plus the contribution from the tail of the Ly$\alpha$ line intercepted by the $uvw2$ filter.
Formally, a least-squares fit assuming a relation $\log F_\gamma = m \log F_\nu + q$ yields $m = 1.567$ and $q = -5.026$ (these are the values for the bisector of the correlations $v = m_1 x + q_1$ and $x = m_2 y + q_2$), with a chance probability $P = 6.4 \times 10^{-7}$.

The correlation with the X-ray flux, as illustrated in Fig. 2, suggests the presence of an X-ray constant component contributing at a level of $\sim 5 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$. On the other hand, the plotted data refer only to the 2009 November–December campaign, while the 'low' state (shown in Fig. 4) shows that there are states with lower X-ray and $\gamma$-ray fluxes (see Table 1 and Table 2). The suspected candidate for this behaviour is the synchrotron self-compton (SSC) component during the 2009 November–December period, as we will discuss in Section 5.1. Applying a least-squares fit to the data of Fig. 2, we find $\log F_\nu = 2.267 \log F_X + 17.512$ (again these are the bisector values) and a chance probability of $P = 5 \times 10^{-7}$.

The correlated variability in the three bands strongly suggests that the corresponding fluxes originate in the same region and by the same population of electrons. This supports the 'one-zone' models.

The fact that $F_\gamma$ varies more than linearly with the optical–UV and the X-ray fluxes is interesting and, at first sight, surprising. Indeed the optical–UV is likely synchrotron emission, while the X-ray flux, having a shape much harder than the optical spectrum, belongs to the same HE hump as the $\gamma$-ray emission. We then expect that $F_\nu$ and $F_X$ vary together, with $F_\nu \propto F_X$. Furthermore, if the $\gamma$-ray emission is produced by inverse Compton scattering with broad-line photons, produced externally to the jet—i.e. it is External Compton (EC) radiation—it is proportional to the number of the emitting electrons, as the synchrotron flux. Variations of the electron number should then result in $F_\gamma \propto F_{\text{opt}}$. Finally, if the SSC process contributes substantially in the X-ray band, $F_X$ is proportional to the square of the number density of the emitting electrons, and then we expect $F_X \propto F_\gamma^2$, just the opposite of what observed. A very similar behaviour has been observed for PKS 1502+106 (Abdo et al. 2010a).

More than linear and even more than quadratic variations of the HE $\gamma$-ray flux with respect to the X-ray flux have been already observed in TeV BL Lacs for relatively short (i.e. weeks) periods of time, as in Mkn 421 (Fossati et al. 2008) and PKS 2155–304 (Aharonian et al. 2009), but in these cases the X-ray emission belongs to the synchrotron part of the spectrum, while the $\gamma$-ray flux is probably SSC emission. Even so, it is not easy to explain a quadratic relation during the decaying phases of the light curves, because this implies short cooling time-scales (Katarzynski et al. 2005), leading Katarzynski & Walczewska (2010) to propose that the $\gamma$-ray flux of the varying component must be diluted by the flux produced by another region.

In conclusion, we have that the $\gamma$-ray flux varies more than the flux at lower energies both in 3C 454.3 (and PKS 1502+106) and in the less powerful BL Lac objects, despite the large differences in the jet power and in the jet environment leading to different emission processes for the $\gamma$-ray photons (i.e. SSC for BL Lacs and EC for 3C 454.3 and other powerful FSRQs). While these similarities deserve further studies, we note here that for powerful blazars we have very short cooling times of the emitting electrons, even at low energies: this at least helps to explain the decaying phases of the light curves, that are instead a problem for TeV BL Lacs. For the specific case of 3C 454.3, we will suggest in the following the likely cause of $F_\gamma$ varying more than $F_X$ and $F_{\text{opt}}$, in terms of an inverse correlation between the dissipated power and the magnetic field.

3.1 Variability and cooling time-scales
Tavecchio et al. (2010) analysed in detail the entire light curve of 3C 454.3 in $\gamma$-rays, including the period of exceptional activity studied here. It is found that the minimum doubling time-scale is between 3 and 6 h (in our observer frame). This result has also been confirmed by Foschini et al. (2010), who studied another flare occurred in early 2010 April, comparable in flux but observed by Fermi/LAT in pointed mode, therefore with denser time coverage and enhanced statistics. From Fig. 2, we can see that also in X-rays (note the decrease at December 6 and at December 12) the variability time-scale is $\sim 1$ d or shorter. This behaviour has two important consequences.

(i) The size of the emitting region must be compact, $R < c t_{\text{var}} (1+z) \approx 7 \times 10^{15} t_{\text{var}} (\delta/20) \text{cm}$. As remarked in Tavecchio et al. (2010), this challenges models in which the dissipation region is at tens of parsecs from the black hole (see e.g. Jorstad et al. 2010), this challenges models in which the dissipation region is at tens of parsecs from the black hole (see e.g. Jorstad et al. 2010), this challenges models in which the dissipation region is at tens of parsecs from the black hole (see e.g. Jorstad et al. 2010), this challenges models in which the dissipation region is at tens of parsecs from the black hole (see e.g. Jorstad et al. 2010), this challenges models in which the dissipation region is at tens of parsecs from the black hole (see e.g. Jorstad et al. 2010), this challenges models in which the dissipation region is at tens of parsecs from the black hole (see e.g. Jorstad et al. 2010), this challenges models in which the dissipation region is at tens of parsecs from the black hole (see e.g. Jorstad et al. 2010), this challenges models in which the dissipation region is at tens of parsecs from the black hole (see e.g. Jorstad et al. 2010), this challenges models in which the dissipation region is at tens of parsecs from the black hole (see e.g. Jorstad et al. 2010), this challenges models in which the dissipation region is at tens of parsecs from the black hole (see e.g. Jorstad et al. 2010), this challenges models in which the dissipation region is at tens of parsecs from the black hole (see e.g. Jorstad et al. 2010), this challenges models in which the dissipation region is at tens of parsecs from the black hole (see e.g. Jorstad et al. 2010), this challenges models in which the dissipation region is at tens of parsecs from the black hole (see e.g. Jorstad et al. 2010), this challenges models in which the dissipation region is at tens of parsecs from the black hole (see e.g. Jorstad et al. 2010), this challenges models in which the dissipation region is at tens of parsecs from (ii) The cooling time $t_{\text{cool}} \leq t_{\text{var}}$ for electrons emitting at $\gamma$-ray and X-ray energies. This favours models in which the dissipation occurs in a region where the high density of photons can ensure a rapid cooling. Again, dissipation close to the black hole is favoured, where the BLR can provide a radiation energy density large enough to have $t_{\text{cool}} < t_{\text{var}}$ even for electrons with random Lorentz factors of a few.

3.2 Contribution of the Lyα and of the accretion disc
At a redshift of $z = 0.859$, the Lyα emission line from the BLR is observed at 2260 Å, within the band of the $uvw2$ filter of UVOT (effective wavelength $\lambda_{\text{eff}} = 2231$ Å; Poole et al. 2008).
The γ-ray brightest of 3C 454.3

In this source the line is bright (rest-frame equivalent width $EW = 74$ Å, according to the observations by Wills et al. 1995), and we wanted to check if it could explain the small excess in the $uvw2$ and $uvw2$ filters that is visible in the SED (Fig. 4). In Fig. 3, we show the 1900–2750 Å portion of the UV spectrum of 3C 454.3 observed by the GALEX satellite in 2008 October, together with the SED points observed in the UVOT filters and the corresponding transmission curves. All data have been dereddened with $A_B = 0.46$ and $R_V = 3.1$, following Raiteri et al. (2008) and assuming the extinction law from Cardelli et al. (1989). A small mismatch is apparent, but many factors can account for it, such as systematics in the flux measurement between the two instruments and the loose simultaneity of the observations performed with the two telescopes. Moreover, a quantitative study on this issue is far beyond the scope of this paper. Fig. 3 shows that the small bump in the portion of the SED observed by the UVOT filters can be partially due to the Lyα emission line shining the $uvw2$, and, at a lower level, the neighbouring filters, especially $uvw2$. This excess was well visible in all our UVOT pointings despite the larger level of the non-thermal contribution. Further, we tried to build a simple model for this portion of the spectrum, as the sum of three components:

(i) the Lyα emission line, modelled as a Gaussian profile, with $\sigma$ and normalization obtained from a fit to the GALEX spectrum;
(ii) the blue bump due to a ‘standard’ accretion disc, assumed constant (see Section 4);
(iii) a variable power-law contribution, representing the synchrotron emission from the jet.

With these three components, we managed to reproduce the SED profile for each UVOT observation we considered. The excess in the $uvw2$ filter that we attributed to the Lyα line was compatible, within the uncertainties, with a constant contribution. This supports Raiteri et al. (2007) when they explain the smaller variability range in the UV band with respect to the optical and infrared (IR) as due to the presence of a blue, stable contribution, becoming more important (relative to the steep synchrotron non-thermal continuum) at higher frequencies. What we emphasize is the presence of two constant components: the accretion disc and the Lyα line.
3.3 The SED of 3C 454.3 at different epochs

In Fig. 4, we show the overall optical to $\gamma$-ray SED of 3C 454.3 at five different epochs during 2009 November and December and an additional one (‘low’) representative of a low $\gamma$-ray state (see Section 2). We can see the large variability amplitude of the $\gamma$-ray flux, whose spectrum is instead remarkably less variable, as noted also in Abdol et al. (2010b). Although it is somewhat harder in the ‘low’ state and on 2009 November 27, it is always characterized by a slope $\alpha_\gamma > 1$ \citep{2010ApJ...718..893D}, so that the peak of the $\gamma$-ray spectrum is at energies smaller than 100 MeV. On the other hand, the X-ray 0.2–10 keV slope and the Swift/BAT data points suggest that the peak cannot be much below 100 MeV.

As discussed above, we can see that the optical–UV flux varies, but less than the $\gamma$-ray flux. At low states, the accretion disc becomes ‘visible’ by flattening the spectrum. The presence of the accretion disc emission has been noted by Raiteri et al. (2007) discussing observations in 2006–2007, which indicate that the disc produced a flux comparable with what is reported in Fig. 4.

As remarked before, also the X-ray flux varied much less than the $\gamma$-ray one during 2009 November–December. On the other hand, in the ‘low’ state, the X-ray flux is much lower (also with respect to the optical), and still very hard.

3.4 The mass of the black hole of 3C 454.3

Gu, Cao & Jiang (2001) estimated $M = 4 \times 10^8 M_\odot$ for the mass of the black hole of 3C 454.3. They used the size of the BLR, $R_{\text{BLR}}$ and the full width at half-maximum (FWHM) of the H$\beta$ line equal to 2800 km s$^{-1}$ (Netzer et al. 1995). To derive the velocity of the clouds, they multiplied the FWHM value by a factor $f = 1.5 (V = fV_{\text{FWHM}})$, according to McClure & Dunlop (2001). The McClure & Dunlop factor $f = 1.5$ was empirically estimated assuming that the clouds belong to two components: one moving randomly and isotropically (that would give $f = \sqrt{3}/2$) and one distributed in a disc-like geometry. To derive the black hole mass through $M = R_{\text{BLR}}V^2G^{-1}$, $R_{\text{BLR}}$ was found using the relation of Kasp et al. (2000):

$$R_{\text{BLR}} \sim 4.2 \times 10^{17} \left\{ \frac{(\lambda L_\lambda)_{5100 \ang} / 10^{45} \text{ erg s}^{-1}}{0.70 \pm 0.03} \right\}^{1/2} \text{ cm},$$

where $(\lambda L_\lambda)_{5100 \ang}$ is the luminosity of the continuum at 5100 Å (rest frame, corresponding to an observed wavelength of 9480 Å). For high-luminosity quasars, the more recent results of Kaspi et al. (2007), obtained using the C IV $\lambda 1549$ line, yield

$$R_{\text{BLR}} \sim 7.8 \times 10^{16} \left\{ \frac{(\lambda L_\lambda)_{1549 \ang} / 10^{45} \text{ erg s}^{-1}}{0.55 \pm 0.04} \right\}^{1/2} \text{ cm}.$$  

The observed luminosity at 2510 Å (corresponding to 1350 Å, rest frame) in a period of low state, not much contaminated by the non-thermal continuum, was $\lambda L_\lambda \sim 4 \times 10^{46}$ erg s$^{-1}$ (from the spectrum taken by the GALEX satellite reported in Fig. 3). This yields $R_{\text{BLR}} \sim 6 \times 10^{17} \text{ cm}$. The FWHM of the C IV line, according to Wills et al. (1995), is 3145 km s$^{-1}$. Assuming an isotropic velocity field, $f = \sqrt{3}/2$, the mass calculated through $M = R_{\text{BLR}}Q^2G^{-1}$ is $M = 3.4 \times 10^5 M_\odot$. Assuming $f = 1.5$, instead, we find $M = 1.2 \times 10^5 M_\odot$, in any case smaller than estimated by Gu et al. (2001). Since the continuum could in fact be contaminated by the non-thermal beamed contribution, these values should be considered as upper bounds. Furthermore, given the uncertainties in these relations, this estimate can give only a rough indication of the black hole mass. In the following, when modelling the SED, we will use $M = 5 \times 10^5 M_\odot$. In the general framework of our model, this is the black hole mass ensuring an observed minimum variability time-scale of $\sim 6$ h, if the jet opening angle in its conical part is 0.1 rad, as assumed for all other blazars analysed in Ghisellini et al. (2010).

4 MODELLING THE SED

To model the SED we have used a relatively simple leptonic, one-zone synchrotron and inverse Compton model. This model, fully discussed in Ghisellini & Tavecchio (2009), has the following main characteristics.

We assume that in a spherical region of radius $R$, located at a distance $R_{\text{d can}}$ from the central black hole, relativistic electrons are injected at a rate $Q(\gamma)$ (cm$^{-3}$ s$^{-1}$) for a finite time equal to the light crossing time $R/c$. For the shape of $Q(\gamma)$, we adopt a smoothly broken power law with a break at $\gamma_b$:

$$Q(\gamma) = Q_0 \left( \frac{\gamma}{\gamma_b} \right)^{-\alpha_1} \left[ 1 + \left( \frac{\gamma}{\gamma_b} \right)^{-\alpha_2} \right].$$  

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 $\theta$, and the Doppler factor is $\delta = 1/\Gamma (1 - \beta \cos \theta)$. 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 per cent of the accretion luminosity from a shell-like distribution of clouds located at a distance $R_{\text{BLR}} = 10^{17} \sqrt{L/\dot{L}_{\text{IR}}}$ cm; (ii) the IR emission from a dusty torus, located at a distance $R_{\text{IR}} = 2.5 \times 10^8 \sqrt{L/\dot{L}_{\text{IR}}}$ cm; (iii) the direct emission from the accretion disc, 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. We instead neglect, for simplicity, the contribution of a possible population of intracloud free electrons. This contribution would be important if the optical depth $\tau$ of these electrons became greater than the covering factor of the emitting line clouds, i.e. $\tau > 0.1$, a rather large value. These free electrons would scatter and re-isotropize the entire disc flux, providing IR radiation, besides optical and UV. The final effect would be to broaden the HE hump, especially below its peak.

All these contributions are evaluated in the blob comoving frame, where we calculate the corresponding inverse Compton radiation from all these contributions, and then transform into the observer frame. For simplicity, the numerical code assumes an abrupt cut-off for the scattering cross-section, equal to the Thomson one for $\gamma h\nu_{300}/m_e c^2 < 1$ and zero above. This approximation provides acceptable results in the calculation of the inverse Compton scattering of the BLR (e.g. Tavecchio & Ghisellini 2008) and starts to fail only at the largest energies probed by LAT, at which scatterings in the full Klein–Nishina regime start to be important (see also Georganopoulos, Kirk & Mastichiadis 2001; Moderski et al. 2005, for a discussion on the importance of the full Klein–Nishina cross-section).

We calculate the energy distribution $N(\gamma)$ (cm$^{-3}$) 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 $e^+e^-$ 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.

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For 3C 454.3, the radiative cooling time of the particles is short, shorter than $R/c$ even for low-energetic particles. This implies that, at lower energies, the $N(y)$ distribution is proportional to $y^{-2}$, while, above $y_\ast$, $N(y) \propto y^{-(\gamma+1)}$. The electrons emitting most of the observed radiation have energies $y_{\text{peak}}$ which is close to $y_\ast$ (but these two energies are not exactly equal, due to the curved injected spectrum).

The accretion disc component is calculated assuming a standard optically thick geometrically thin Shakura & Sunyaev (1973) disc. The emission is locally a blackbody, with a temperature profile given e.g. in Frank, King & Raine (2002). Since the optical–UV is the sum of the accretion disc and the jet non-thermal components, there is some degeneracy when deriving the black hole mass and the accretion rate, even in the lowest state, for which the disc is best visible. On the other hand, we can take as a guideline the value of the black hole mass derived in Section 4.1, implying then a very large accretion rate. We also note that in modelling the optical–UV region, one should also consider other thermal components, such as the other emission lines and the Balmer continuum from the BLR. However, all these components are expected to be much less bright than the Ly$\alpha$ emission line, included in the fit. It is also possible that the disc emission spectrum is different than that expected by the Shakura & Sunyaev model; however we use the latter, built on robust theoretical basis.

We model at the same time the thermal disc (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 disc 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 disc luminosity).

By estimating the physical parameters of the source, we can calculate the power that the jet carries in the form of radiation ($P_i$), 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 Constraints on the model parameters

We briefly discuss the constraints that we can put on our modelling.

(i) The size $R$ of the emitting region must be compact, in order to vary with the observed short time-scale. In the adopted model, this corresponds to a location of a jet dissipation region $R_{\text{disk}} \sim c t_{\text{obs}} \delta / [(1+z) \psi] \sim 7 \times 10^{16} t_{\text{obs}} (6/20) / \psi_{-1} \text{ cm}$, if the jet opening angle is $\psi = 0.1 \psi_{-1}$.

(ii) The short variability time-scale and the large disc luminosity imply $R_{\text{disk}} < R_{\text{BLR}}$: the dissipation occurs within the BLR.

(iii) If so, the relevant radiation energy density is provided by the BLR photons, with energy density $U'_{\text{BLR}} \sim f_{\text{BLR}} L_d \Gamma^2 / (4\pi R_{\text{BLR}}^2 c)$. Setting $f_{\text{BLR}} = 0.1$ and using $R_{\text{BLR}} = 10^{17} L_d^{1/4} \text{ cm}$, the resulting $U'_{\text{BLR}} \sim \Gamma^2 / (12\pi)$, i.e. the dependence on $L_d$ and $R_{\text{BLR}}$ drops out. As a consequence, the Lorentz factor of the electrons cooling in a time $R/c$ is $(U_B + U'_{\text{BLR}})$ are the magnetic and the synchrotron energy densities:

$$y_{\text{cool}} = \frac{3 m_e c^2}{4 \pi^2 U'_{\text{BLR}} R([1 + (U_B + U'_{\text{syn}}) / U'_{\text{BLR}}])} \sim \frac{(\Gamma/20)^2 R_{\text{disk}} ([1 + (U_B + U'_{\text{syn}})] / U'_{\text{BLR}})^1/2.}$$

Therefore the radiative cooling is efficient for all but the lowest energy electrons.

(iv) The bulk Lorentz factor $\Gamma$ and the Doppler factor $\delta$ are constrained by the observed superluminal motion at the very long baseline interferometry (VLBI) scale. Jorstad et al. (2005) find different components moving with different apparent velocities $\beta_{\text{app}}$, from a few more to 20, for observations performed between 1998 and 2001, resulting in different bulk Lorentz factors (from 10 to 25) and different orientations (viewing angles from 0° to 4°), resulting in different Doppler factors ($\delta$ from 14 to 30). More recent observations by Lister et al. (2009) found $\beta_{\text{app}} = 14.2 \pm 0.8$, consistent with the previous findings.

(v) The soft slope of the $\gamma$-ray spectrum and the hard slope of the X-ray spectrum constrain the peak of the HE component $h_{\nu_{\text{peak}}}$ of the SED to lie below 100 MeV (but close to this value). For the EC process, the peak is made by the most relevant electrons scattering the Ly$\alpha$ seed photons. They must have a Lorentz factor $y_{\text{peak}}$ given by

$$v_c \sim y_{\text{peak}} h_{\nu_{\text{sync}}} \frac{\Gamma \delta}{1 + z} \sim 210 \frac{h_{\nu_{\text{sync}}}}{100 \text{MeV}} \frac{1/2}{\delta} \frac{\Gamma}{400}.$$  

This implies that the emission at and above the $\gamma$-ray peak is in fast cooling (i.e. that the cooling time is shorter than $R/c$).

(vi) Since the bolometric luminosity is dominated by the $\gamma$-ray emission, this limits the injected power in the form of relativistic electrons. The fast cooling regime ensures that almost all the injected power is converted into radiation. We then have $P_{\text{ej}} \approx L_x / \delta^3$.

(vii) In general, the value of the magnetic field in the emitting region is derived by the level of the synchrotron emission. However the peak of the synchrotron spectrum, and hence its bolometric luminosity, lies in the unobserved mm–far-IR frequency range. A more robust constrain comes from the soft X-ray band, where we have the contribution of the EC and SSC components. Their spectrum is different (the SSC is softer). Increasing the magnetic field $B$ increases the SSC component. The $B$ field is then found by reproducing the observed flux and shape of the X-ray spectrum.

(viii) The observed soft shape of the $\gamma$-ray and optical–UV spectra (once accounting for the contribution of the accretion emission, important in the low states) constrains the index $s_2$ of the energy distribution of the injected electrons. Since the cooling is almost complete (i.e. almost all electrons cool in $R/c$), the shape of the emitting distribution, below $y_{\text{peak}}$, is $\propto y^2$, almost independent of $s_1$ (if $s_1 < 2$). On the other hand, the details of the curvature around $y_{\text{peak}}$ and the distribution below $y_{\text{cool}}$ do depend on $s_1$. This index is then found by reproducing the X-ray spectrum (and the Swift/BAT point).

### 5 RESULTS

Fig. 4 shows the results of our modelling for the six simultaneous SEDs for different epochs, while Table 4 lists the used parameters. Fig. 5 shows the same SEDs and models, but extending the frequency axis to the radio band and showing some archival data, to put the SEDs analysed here in context.
Table 4. For all models, we have assumed a viewing angle $\theta = 1.8$ and a bolometric luminosity of the accretion disc $L_{\text{disc}} = 6.75 \times 10^{46}$ erg s$^{-1}$. The black hole mass is assumed to be $M = 5 \times 10^8 M_\odot$, so the disc luminosity is the 90 per cent of the Eddington value, and the mass accretion rate is $M_\dot{\text{a}} = 14.78 M_\odot$ yr$^{-1}$ (assuming an efficiency $\eta = 0.08$). The size of the emitting blob, for the assumed distances $R_{\text{dis}}$ from the black hole, is always $\psi R_{\text{dis}}$, with $\psi = 0.1$. We assume that the 10 per cent of the disc luminosity is reprocessed by the BLR and re-emitted as broad lines at a distance $R_{\text{BLR}} = 8.2 \times 10^{17}$ cm for all models. Another 30 per cent of the disc luminosity is reprocessed and re-emitted as IR radiation by a torus, located at $R_{\text{tor}} \sim 2 \times 10^{19}$ cm. The minimum observed variability time-scale $\tau_{\text{var}}$ is in hours and is defined as $\tau_{\text{var}} = R(t+\Delta)/c$. Powers are in units of erg s$^{-1}$. Size and distances in units of $10^{15}$ cm. Magnetic field $B$ in Gauss. Outflow mass rates $M_{\text{out}}$ in $M_\odot$ yr$^{-1}$.

| $R_{\text{dis}}$ | $P_e^{\psi}$ | $B$ | $\Gamma$ | $\gamma_b$ | $\gamma_{\text{max}}$ | $s_1$ | $s_2$ | $R_{\text{dis}}/R_s$ | $R_{\text{abs}}$ | $\gamma_{\text{peak}}$ | $\delta$ | $\tau_{\text{var}}$ | $\log P_f$ | $\log P_g$ | $\log P_c$ | $\log P_B$ | $M_{\text{out}}$ |
|-----------------|-------------|-----|--------|----------|-----------------|-----|-----|-----------------|-------------|--------------|-----|----------|-------------|-------------|-------------|-------------|-------------|-------------|------------|
| 132             | 0.012       | 6.35| 15     | 400      | 2.0e3          | 1.2 | 3.4  | 880             | 13.2        | 149          | 24.5| 5.0     | 45.35       | 47.08       | 44.62       | 45.84       | 0.14         | 1.08        |
| 156             | 0.054       | 5.79| 15     | 340      | 3.4e3          | 1.4 | 4.0  | 1040            | 15.6        | 95.8         | 24.5| 5.9     | 45.98       | 47.97       | 45.40       | 45.84       | 1.30          | 1.33        |
| 174             | 0.083       | 4.57| 17     | 800      | 2.8e3          | 1.45| 3.9  | 1160            | 17.4        | 206.6        | 26.4| 6.1     | 46.33       | 48.11       | 45.51       | 45.84       | 1.01          | 1.33        |
| 150             | 0.09        | 5.24| 18     | 600      | 3.0e3          | 1.2 | 4.3  | 1160            | 15.0        | 203          | 26.4| 6.1     | 46.42       | 48.01       | 45.51       | 45.88       | 1.01          | 1.01        |
| 174             | 0.145       | 4.43| 19.6   | 350      | 2.8e3          | 1.2 | 4.3  | 1150            | 17.6        | 176          | 27.3| 5.1     | 46.72       | 48.09       | 45.63       | 45.94       | 1.08          | 1.08        |
| 174             | 0.13        | 4.49| 19.7   | 430      | 3.0e3          | 1.2 | 4.3  | 1160            | 17.7        | 144          | 28.4| 5.7     | 46.66       | 48.37       | 45.76       | 45.96       | 2.09          | 2.09        |

The model successfully reproduces the data from the optical to the $\gamma$-ray band, using the guidelines explained in Section 4.1. The large variations of the $\gamma$-ray luminosity are obtained by mainly varying the power injected in relativistic electrons (by a factor of 10 from the ‘low’ to the highest state, and by a factor of 3 in the restricted period from November 6 to December 2), and the bulk Lorentz factor (from 15 to 20). These are the main changes. Besides them, there are minor changes in the location of the dissipation region (hence, in the size of the emitting region) by less than a factor of 1.4, and in the parameters of the injected electron distribution (i.e. $\gamma_b$ changes by a factor of $\sim 2$, and also $s_1$ changes somewhat). These changes are required to fit the X-ray spectrum, while the changes in the $s_2$ parameter are necessary to account for the (small) changes of the $\gamma$-ray and the optical–UV spectra. Although minor, these changes have a relatively strong impact on the total jet power, because $\gamma_b$ and $s_1$ control the total amount of electrons present in the source, thus also the number of cold protons, if we assume one proton per electron. Indeed, the maximum value of $P_e$ is obtained on December 3, not at the maximum of the $\gamma$-ray flux (occurring at December 2, when there is also the maximum of the $\gamma$-ray facility in orbit in 2005, so we do not know the $\gamma$-ray flux during the optical flare, interpreted by Katarzynski & Ghisellini (2007; see also Ghisellini et al. 2007) as a dissipation event occurring relatively close to the black hole, where the magnetic energy density can be of the same order of the radiation energy density as seen in the comoving frame. In this case $L_{\text{syn}} \sim L_{\text{EC}} \sim L_{\gamma}$, and we do not need an extraordinary increase of the total power budget to explain this extraordinary optical flare that can occur without a corresponding large increase of the $\gamma$-ray flux (and the bolometric one; in this sense the model can be thought as ‘economic’, i.e. assuming the lowest possible power budget). On the contrary, the 2009 $\gamma$-ray flare does change the bolometric luminosity by a large factor, without inducing a correspondingly dramatic increase of the optical flux. The results of the modelling presented here explain this behaviour by having a larger power dissipated in regions more distant than in the 2005 flare, with relatively smaller magnetic field and larger bulk Lorentz factors.

Fig. 5 also shows that the ‘low’ Fermi/LAT state is lower than the $\gamma$-ray flux detected by EGRET in January 1992 and that the X-ray flux and spectrum detected by Swift/XRT for the ‘low’ state superpose exactly to the BeppoSAX data of 2000 June 5–6 (discussed in Tavecchio et al. 2002).

5.1 $\gamma$-ray versus X-ray and $\gamma$-ray versus optical flux correlations

In Section 3, we showed that the $\gamma$-ray flux varies almost quadratically with the optical and X-ray fluxes. In the framework of
is the total observed non-thermal luminosity \( R_F \) (Top: the magnetic field \( B \) in erg s\(^{-1}\)). \( \Gamma \) implies a larger final \( \Gamma' \) when \( \Gamma_1 \) is lower. \( 5 \) should change as \( P_e \) is a function of \( \Gamma R_{\text{diss}} \), and how \( R_{\text{diss}} \) for the different states. The correlation, since the contribution of the SSC component \( \gamma \) is inversely correlated with \( R_{\text{diss}} \) \( - \) \( \sim \) \( L_{\gamma} \) \( \cdot \) \( e - \) \( \gamma \). \( P_{\text{jet}} \) may be partly a coincidence, but since \( \Gamma_1 \) is achieved, but since \( \Gamma \) is larger, \( R_{\text{diss}} \) and \( \Gamma \) are larger, \( P_B \) at the dissipation region may vary much less than \( P_{B,0} \) \( \sim \) \( P_{\text{jet}} \propto L_{\gamma} \).

5.2 The power of the jet

It is interesting to investigate if the extraordinary \( \gamma \)-ray flare corresponds to a real enhancement of the power carried by the jet or if it originates by an enhanced efficiency in converting the jet power into radiation, or if it is due to an increased Doppler factor \( \delta \), making the observed flux to increase even if the jet power remains constant. The nearly model-independent quantity connected to the jet power is \( P_t \), the power that the jet spends to produce the radiation we see. Using \( U_{\text{rad}} = L'/(4\pi R^2 c) \), we can rewrite equation (4) as

\[
P_t = L' \frac{\Gamma^2}{4} = L \left( \frac{\Gamma^2}{4\delta^2} \right) \sim L \frac{1}{4\delta^2}.
\]

where \( L \) is the total observed non-thermal luminosity (\( L' \) is in the comoving frame) and \( U_{\text{rad}} \) is the radiation energy density produced by the jet (i.e. excluding the external components). The last equality assumes \( \theta_e \propto \Gamma_1 \). This quantity is almost model-independent, since it depends only on the adopted \( \delta \), that can be estimated also by other means, namely superluminal motions. In Table 4 we list the values of \( P_t \) for the different states. The maximum is on December 2, the day of the maximum \( L_{\gamma} \), when \( P_t = 5.2 \times 10^{46} \) erg s\(^{-1}\). This value can be compared with the accretion luminosity, that we assumed constant during the entire period and equal to \( L_d = 6.75 \times 10^{46} \) erg s\(^{-1}\). The power \( P_t \) can be considered as a very robust lower limit to the total jet power \( P_{\text{jet}} = P_B + P_e + P_p \). If the entire \( P_{\text{jet}} \) is used to produce the radiation we see (i.e. \( P_{\text{jet}} = P_t \)), then the jet would necessarily decelerate and there would be no VLBI superluminal knots, nor any extended radio emission.

Table 4 lists also the value if \( P_B \) and \( P_e \). They are smaller than \( P_t \). The fact that \( P_e < P_t \) may seem strange at first sight, since the jet power is produced by the electrons, so how can they have less power that what they transform in radiation? The answer is that the radiative cooling time is shorter than \( R/c \), so electrons need to be injected continuously, at least for a time \( R/c \). To estimate \( P_e \), we count electrons (and their energy) forming the \( N(\gamma) \) (cm\(^{-3}\)) energy distribution after solving the continuity equation, not the ones injected. An example can clarify this point: assume to inject the same energy distribution \( Q(\gamma) \) (cm\(^{-3}\) s\(^{-1}\)). In case \( A \) the radiative cooling \( \gamma \) is strong, in case \( B \) it is weak. The particle density \( N(\gamma) \) is always proportional to \( [\int Q(\gamma) d\gamma]/\gamma \), therefore in case \( A \), \( N(\gamma) \) is smaller than in case \( B \). This despite the fact that in case \( A \) we have produced more radiation, since the cooling is stronger.

This implies that there must be a ‘reservoir’ of power able to energize electrons that in turn produce \( P_t \). The simplest solution is to assume that this ‘reservoir’ is provided by protons. The listed values of \( P_t \) assume one proton per electron. The implication is that electron–positron pairs cannot be energetically dominant, even if we cannot exclude that they outnumber primary electrons (but not by a large factor). For a more detailed discussion about this point, see Sikora & Madejski (2000) and Celotti & Ghisellini (2008). We summarize here the arguments in Celotti & Ghisellini (2008). If pairs are dynamically important, they must outnumber protons and also the emitting leptons by a large factor. Although possible in principle, this solution poses the problem of the origin of this large number of pairs. If they have been created in the same emitting region (e.g. by \( \gamma-\gamma \) collisions), then we should see (i) a cut-off in...
the spectrum and (ii) some reprocessed radiation in X-rays (since the pairs are born relativistic). The level of this reprocessed radiation must be of the same order of the absorbed luminosity (i.e. it is large and should be well visible). If, instead, the pairs are created from the start, we can calculate how many we need. In powerful sources (as 3C 454.3) this number corresponds to an initial pair optical depth of \( \tau \sim 5 \) at the Schwarzschild radius \( r_s \) greater than unity. If initially cold, the pairs quickly annihilate, and the surviving ones are not enough (to be dynamically important). If they are hot, they emit. At the start of the jet, close to the accretion disc, the radiation energy density and the magnetic field make them to cool very rapidly. So they become cold, and annihilate (besides producing radiation we do not see).

Assuming then that \( P_{\gamma} \) is a good proxy for the real \( P_{\text{jet}} \), we see that during 2009 November and December the jet power varied only by a factor of 2, while \( L_{\gamma} \) varied by a factor of \( \sim 10 \). This implies that the jet became more efficient in transforming its power into radiation, rather than becoming more powerful. For the 'low' state, instead, the estimated value of \( P_{\gamma} \sim 10^{47} \text{ erg s}^{-1} \) is a factor of 10 less than in November 27, with \( L_{\gamma} \) being a factor of 4 weaker. To summarize, the total excursion (from 'low' state to 2009 December 3) of \( P_{\gamma} \) is a factor of 20, not very different from the total amplitude of \( L_{\gamma} \) (factor of \( \sim 30 \)). But restricting the period from November 6 to December 3, the jet power is quasi-constant, while \( L_{\gamma} \) varied by a factor of 10.

5.3 Jet power versus disc luminosity

The disc luminosity is \( L_d = 6.7 \times 10^{46} \text{ erg s}^{-1} \), comparable to \( P_r \). The jet power must be greater than \( P_r \) and therefore greater than \( L_d \). This is one of the most important outcomes of having followed 3C 454.3 during its major \( \gamma \)-ray flare.

Table 4 lists the value of the outflowing mass rate, estimated through \( P_{\gamma} = \Gamma M_{\text{out}} c^2 \). Since \( \Gamma \) varies moderately (between 15 and 20) while \( P_{\gamma} \) varies by a factor of 10, we have that also \( M_{\text{out}} \) varies by an order of magnitude considering the entire time-span, and only by a factor of 2 in 2009 November–December. In this period, it is of the order of 1 solar mass per year. We can compare this value with the accretion mass rate \( M_{\text{in}} \), that we can derive through \( L_d = \eta M_{\text{in}} c^2 \). Assuming \( \eta = 0.08 \), a disc luminosity \( L_d = 6.75 \times 10^{46} \text{ erg s}^{-1} \) gives \( M_{\text{in}} = 14.8 \text{ M}_{\odot} \text{ yr}^{-1} \), about a factor of 10 greater than \( M_{\text{out}} \).

If the disc emits at a constant level, with a constant \( M_{\text{in}} \), we are forced to conclude that the link between the accretion rate and the jet power is not determined by \( M_{\text{in}} \), or, rather, that this is not the only important quantity in producing \( P_{\text{jet}} \). For the ensemble of bright FSRQs detected by Fermi, in fact, the disc luminosity does correlate with \( P_{\text{jet}} \), even taking out the effect of a common redshift dependence in the two quantities (see Fig. 7 and the discussion in Ghisellini et al. 2010). Since the spin of the black hole of 3C 454.3 is constant, the likely quantity that modulates \( P_{\text{jet}} \) in 2009 November–December is the value of the magnetic field in the vicinity of the black hole horizon. If we assume that \( P_{\gamma,0} = P_{\text{jet}} \) at the Schwarzschild radius \( r_s \), the magnetic field must be

\[
B_0 = B(r_s) = 10^5 P_{\gamma,0,48}^{1/2} \left( \frac{5 \times 10^8 \text{ M}_{\odot}}{M} \right)^{1/2} \text{ G}.
\]

In turn, we can check if the magnetic energy density \( B_0^2/(8\pi) \) can be equated to \( \rho c^2 \), the mass energy density of the accreting matter

![Figure 7](https://academic.oup.com/mnras/article-abstract/410/1/368/1034166) The observed \( \gamma \)-ray luminosity \( L_{\gamma} \) (top panel), the power \( P_r \) spent by the jet to produce the radiation we see (mid panel) and the total jet power \( P_{\text{jet}} \) (bottom panel) as a function of the accretion disc luminosity \( L_d \). The filled circles correspond to the six states of 3C 454.3 analysed in this paper, while the empty squares correspond to all the FSRQs detected in the first three months of the Fermi/LAT all-sky survey analysed by Ghisellini et al. (2010).
close to the Schwarzschild radius. We can write

\[ \dot{M}_\text{in} = 4\pi R_\odot^2 \frac{H}{R} \rho V_\text{r} \rightarrow \]

\[ \rho c^2 = \frac{\dot{M}_\text{in} c^2}{4\pi R_\odot^2 (H/R) V_\text{r}} \rightarrow \]

\[ = \frac{4\pi \eta R_\odot^2 (H/R) V_\text{r}}{P_{\text{jet}}^0 (4\pi R_\odot^2 \rho_\text{r}^0)} \]

(9)

where \( V_\text{r} \) is the radial inflowing velocity and \( 2H \) is the total height of the disc at the Schwarzschild radius. The above equation shows that if \( \rho c^2 \sim B_\odot^2/(8\pi) \) and \( P_{\text{jet}}/L_\text{d} \sim 10 \), then \( \rho_\text{r}(H/R) \sim 0.3 \), i.e. not an unreasonable value.

### 5.4 Is 3C 454.3 exceptional?

We finally ask if 3C 454.3 is exceptional, or instead if there are other blazars reaching comparable values of \( L_\gamma \) and of \( L_\gamma/L_\text{d} \). To answer, we can compare the flaring state of 3C 454.3 with all blazars of known redshift of the first three months Fermi/LAT all-sky survey (Abdo et al. 2009c), analysed in Ghisellini et al. (2010), as done in the top panel of Fig. 7. We alert the reader that in Ghisellini et al. (2010) we have considered the peak flux values there would be a few FSRQs of 3C 454.3 in high state (one example is PKS \( \rightarrow 379 \)).

\[ \text{Swift} \]

\( \beta_\text{r} \rho_\text{c} \approx \text{comparable to 3C 454.3.} \]

\[ \begin{align*}
\text{368–380} & \text{V} \\
\text{2010 RAS, MNRAS} & \text{on 29 July 2018}
\end{align*} \]

\[ \text{Downloaded from https://academic.oup.com/mnras/article-abstract/410/1/368/1034166} \]

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