THE REMARKABLE $\gamma$-RAY ACTIVITY IN THE GRAVITATIONALLY LENSED BLAZAR PKS 1830–211

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ABSTRACT

We report the extraordinary $\gamma$-ray activity ($E > 100$ MeV) of the gravitationally lensed blazar PKS 1830–211 ($z = 2.507$) detected by AGILE between 2010 October and November. On October 14, the source experienced a factor of $\sim 12$ flux increase with respect to its average value and remained brightest at this flux level ($\sim 500 \times 10^{-8}$ photons cm$^{-2}$ s$^{-1}$) for about four days. The one-month $\gamma$-ray light curve across the flare showed a mean flux $F(E > 100$ MeV$) = 200 \times 10^{-8}$ photons cm$^{-2}$ s$^{-1}$, which resulted in a factor of four enhancement with respect to the average value. Following the $\gamma$-ray flare, the source was observed in near-IR (NIR)–optical energy bands at the Cerro Tololo Inter-American Observatory and in X-Rays by Swift/X-Ray Telescope and INTEGRAL/IBIS. The main result of these multifrequency observations is that the large variability observed in $\gamma$-rays does not have a significant counterpart at lower frequencies: no variation greater than a factor of $\sim 1.5$ appeared in the NIR and X-Ray energy bands. PKS 1830–211 is then a good $\gamma$-ray only flaring” blazar showing substantial variability only above 10–100 MeV. We discuss the theoretical implications of our findings.

Key words: galaxies: active – galaxies: jets – quasars: general – quasars: individual (PKS 1830–211) – radiation mechanisms: non-thermal

1. INTRODUCTION

PKS 1830–211 is a high redshift blazar ($z = 2.507$; Lidman et al. 1999) gravitationally lensed by a spiral galaxy at $z = 0.886$ (Wilkind & Combes 1996), as showed by the two radio lobes located 1′ apart from each other (Lovel et al. 1998). The lensed counterparts were observed also in near-IR (NIR) and optical energy bands by the Hubble Space Telescope and the Gemini Observatory (Courbin et al. 2002). The source was observed in X-Rays by both XMM-Newton and Chandra, allowing us to study the complicated soft X-Ray behavior in detail, probably due to absorption (Dai et al. 2008). Moreover, the source presents a soft $\gamma$-ray energy spectrum ($\Gamma = 2.56$) as detected by EGRET (Hartman et al. 1999) and recently confirmed by the Fermi Large Area Telescope (LAT; Abdo et al. 2010).

The modeling of the spectral energy distribution (SED) of this blazar (De Rosa et al. 2005) led to the tentative classification of PKS 1830–211 as an MeV blazar (the inverse Compton peak lies below 100 MeV; Sikora et al. 2002), with the caveat that the entire data set was not simultaneous. In particular, the SED was interpreted in the standard framework of a one-zone leptonic model where the seed photons responsible for inverse Compton peak should be originated within the torus surrounding the central engine.

The source has been extensively monitored in hard X-Rays by the Imager on Board the International Gamma-Ray Astrophysics Laboratory Satellite (INTEGRAL/IBIS) for a seven-year-long period, during which no significant variability has appeared on either short (daily) or longer (monthly) timescales (Zhang et al. 2008).

Since its launch, AGILE (Tavani et al. 2009) has detected one $\gamma$-ray flare ($F(E > 100$ MeV$) = (160 \pm 50) \times 10^{-8}$ photons cm$^{-2}$ s$^{-1}$) of PKS 1830–211 in 2009 October (Striani et al. 2009), which resulted in an enhancement by a factor of three compared with the one-week average flux detected before the flare ($F(E > 100$ MeV$) = 40 \times 10^{-8}$ photons cm$^{-2}$ s$^{-1}$).

One year later, Fermi/LAT detected a significant enhancement of the $\gamma$-ray emission ($F(E > 100$ MeV$) = (520 \pm 110) \times 10^{-8}$ photons cm$^{-2}$ s$^{-1}$ and $F(E > 100$ MeV$) = (1400 \pm 500) \times 10^{-8}$ photons cm$^{-2}$ s$^{-1}$ on one-day and 6 hr timescales, respectively (Ciprini 2010), resulting in increases by factors of about 12 and 35 with respect to the average value reported by Abdo et al. (2010). Moreover, AGILE detected a prolonged $\gamma$-ray activity two days after the flare reported by Fermi (Donnarumma et al. 2010).

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In this Letter, we present the results obtained by multifrequency monitoring of PKS 1830–211 from the NIR to γ-ray energy bands. We describe in detail the multi-λ data analysis and a possible interpretation of the SED of this object to reconcile the average γ-ray activity with the γ-ray enhancement. We adopt a Λ-CDM cosmology with the parameters $h = 0.71$, $\Omega_m = 0.27$, and $\Omega_\Lambda = 0.73$.

2. THE MULTIWAVELENGTH CAMPAIGN

2.1. AGILE Observations

AGILE/GRID data were analyzed using the Build-20 software. Well-reconstructed γ-ray events were selected using the FM3.119 filter. All the events collected during the passage in the South Atlantic Anomaly were rejected. We filtered out Earth-albedo γ-rays, rejecting photons coming from a circular region of radius 80° and centered on the Earth. A one-month-long γ-ray light curve (two-day time bin, see Figure 1) across the γ-ray flare reported by Fermi/LAT was produced between 2010 October 8 00:00 UT and November 8 00:00 UT (MJD 55484–55509) using the standard AGILE maximum likelihood procedure. We obtain a mean flux on the whole integration time of $F(\gamma > 100$ MeV) $= (200 \pm 29) \times 10^{-8}$ photons cm$^{-2}$ s$^{-1}$, which is a factor of about four higher than the flux reported in the first Fermi catalog. We note that this γ-ray enhancement represents a $5\sigma$ excess with respect to its value in steady state as detected by AGILE $F(\gamma > 100$ MeV) $= (32 \pm 8) \times 10^{-8}$ photons cm$^{-2}$ s$^{-1}$; F. Verrecchia et al. 2011, in preparation).

We extracted the γ-ray spectrum between 100 MeV and 1 GeV, discarding the energy channels above 1 GeV due to poor statistics. The AGILE spectrum is well fitted by a power law with a photon index of $2.05 \pm 0.17$ (all the errors reported in this Letter are at 1σ, unless otherwise stated).

As shown in Figure 1, the source remained at a flux level of $\sim 200 \times 10^{-8}$ photons cm$^{-2}$ s$^{-1}$ on a one-month timescale. A clear enhancement emerged on October 14 (MJD 55483) that lasted about four days. The two-day binned AGILE data showed that the source reached its maximum of $F(\gamma > 100$ MeV) $\sim (500 \pm 130) \times 10^{-8}$ photons cm$^{-2}$ s$^{-1}$ on October 15 (MJD 55484.75 ± 0.7); the estimate of this epoch accounts for the bias introduced by the choice of the starting time ($T_{\text{start}}$) and the binning adopted to obtain the light curve. This was done by operating four translations of $T_{\text{start}}$ (by 0, 0.5, 1, and 1.5 days) in the light curve.

We also extracted the γ-ray spectrum during the four-day flare, obtaining a power-law photon index $\Gamma = 2.40 \pm 0.28$. Because of the poor statistics on this short duration, it was not possible to infer whether any hardening or softening occurred during this flare, the photon indices being compatible within 1σ.

In Section 3, we will focus on the one-month γ-ray enhancement and on the four-day flare detected between October 14 and 18 (horizontal lines in Figure 1).

2.2. X-Ray Observations

2.2.1. X-Ray Observations

During the γ-ray flare of PKS 1830–211 in 2010 October, INTEGRAL (Ubertini et al. 2003) was monitoring the Galactic bulge region (since INTEGRAL AO-3, Kuulkers et al. 2007 have been observing this region regularly during all visibility periods). The monitoring across the γ-ray flare (MJD 55479 – 55491, 2010 October 10–22) did not allow for the detection of PKS 1830–211, and an upper limit of $\sim 3 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ (accounting for the 15° off-axis position of the source) was obtained with a net exposure of 200 ks (October 14–18).

Since the hard X-Ray average flux (20–40 keV) is 2.6 mcrab ($1.95 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$; Bird et al. 2010), we may exclude variations greater than a factor of 1.5 in this energy band. Therefore, in this Letter we use the INTEGRAL/IBIS data collected in the fourth IBIS survey (Bird et al. 2010) consisting of 7355 Science Windows (lasting about 2000 s each), performed from the beginning of the mission in 2002 November.
up to 2008 April and including all available public and Core Programme data. The total on-source exposure is 4258 ks. IBIS/ISGRI images for each available pointing were generated in various energy bands using the INTEGRAL Science Data Center offline scientific analysis software OSA (Goldwurm et al. 2003) version 7.0. Then all images were mosaicked to create significance maps at the revolution level (each revolution lasting about three days) and for the all available pointings. Count rates at the position of the source were extracted from individual images in order to provide light curves in various energy bands; from these light curves, we extracted and combined the average fluxes in order to produce an average source spectrum (see Bird et al. 2010 for details). The derived hard X-Ray spectrum is well fitted by a power law with $\Gamma = 1.56 \pm 0.14$, providing a flux of $1.4 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ and $2.7 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ in 20–40 keV and 40–100 keV, respectively. It is worth noting that this spectrum represents the best coverage in hard X-Rays of PKS 1830–211.

2.2.2. The Swift Observations

Following the $\gamma$-ray flare, the Swift/X-Ray Telescope (XRT; Gehrels et al. 2005) pointed at PKS 1830–211 12 times between 2010 October 15 and 27 (MJD 55484–55496) with net exposures ranging between 1000 and 4000 s. The XRT level 1 data were processed with the standard procedures (xrtpipeline v.0.12.2). We selected photon counting mode data with the standard 0–12 grade selection, and source events were extracted in a circular region of aperture of ~40″, and the background was estimated in different same-sized circular regions far from the source. We created response matrices through the xrtmkarf task. As for spectra with very few counts, we applied Cash statistics and we rebinned the remaining spectra in order to have at least 30 counts per bin, excluding from the fit the channels with energies below 0.3 keV and above 10 keV. We fitted each spectrum with a continuum power law absorbed both with a Galactic column density ($N_H^{\text{Gal}} = 2.6 \times 10^{21}$ cm$^{-2}$; Stark et al. 1992) and an additional absorber located at a redshift $z = 0.886$. Due to the short exposure for each observation, the fitting procedure resulted in a degeneracy between $N_H^*$ and $\Gamma$. We found the values of $N_H^*$ by combining all the spectra together in full agreement with the previous measurement obtained with Chandra observations; therefore we decided to fix $N_H^*$ to this value, i.e., $1.94 \times 10^{22}$ cm$^{-2}$. All data sets are well reproduced by this model, with $\chi^2$ degrees of freedom ranging between 0.9 and 1.1. The best-fit values of the photon index range between $\Gamma = 1.0 \pm 0.3$ and $1.4 \pm 0.2$ with absorbed fluxes in 0.3–10 keV between $2.1 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$, all consistent within $1\sigma$ given the large uncertainties. On 2010 October 15, the day overlapping the $\gamma$-ray flare, the absorbed flux in 0.3–10 keV is $1.12^{+0.07}_{-0.06} \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ at a 90% confidence level. We note that these fluxes are very consistent with the ones reported by De Rosa et al. (2005), ruling out that any significant variation occurred during the high $\gamma$-ray activity (Figure 1). On the time interval of the $\gamma$-ray enhancement (2010 October 15–18), the full-band-detected count rates are between $0.095^{+0.01}_{-0.009}$ and $0.148^{+0.009}_{-0.009}$ counts s$^{-1}$, showing a variation amplitude that is less than a factor of 1.6.

2.3. Optical Monitoring: SMARTS Consortium

Optical and infrared data on PKS 1830–211 were obtained using the 1.3 m telescope at the Cerro Tololo Inter-American Observatory under the Small and Moderate Aperture Research Telescope System (SMARTS) program. We obtained simultaneous data in the optical R and infrared J bands using the ANDICAM instrument, allowing the acquisition of data from 0.4 to 2.2 μm. Our data set consists of 8 R-band and 17 J-band images, taken between 2010 October 16 and 27 (MJD 55485–55496). Images were taken approximately every three nights, with exposure times of 400 to 600 s in R and 90 to 600 s in J. Both the optical and IR data were flat-fielded, bias-subtracted, and overscan-corrected using standard IRAF packages. Single exposures were not sufficient to detect the object in either wave band, nor were summations of the images determined using standard IRAF packages. We estimate a limiting magnitude of 21.5 in R and 17.6 in J, based on the combined images and the magnitudes of field stars acquired from the Two Micron All Sky Survey. The observations performed during the four-day $\gamma$-ray flare resulted in a limiting magnitude 17.6 and 19 in J and R, respectively. The J magnitude limit during the flare period remained unchanged from the longer summation due to the sky limit already having been reached by the shorter exposure time. We note that our limit magnitude could be contaminated by the star S1 located 1″ from PKS 1830–211 (Meylan et al. 2005) and unresolved by SMARTS. Nevertheless, no enhancement at or above two standard deviations of the background (sky) variance was detected within 2″ of the position of PKS 1830–211. Therefore, by comparing our limiting magnitude in J with the photometric data of PKS 1830–211 ($J = 18.04$), we exclude variation >1.5 in the J band.

3. DISCUSSION

Here, we discuss the SED modeling of the blazar PKS 1830–211 during the high $\gamma$-ray state observed between 2010 October and November. Multifrequency observations were activated to follow the $\gamma$-ray flare covering NIR–optical (SMARTS), and soft and hard X-Ray energy bands (Swift/XRT and INTEGRAL/IBIS, respectively). The main results obtained during this multifrequency campaign are that the high and unusual activity recorded in $\gamma$-rays seems to have no significant counterpart at lower frequencies. In detail, the simultaneous NIR–optical and soft and hard X-Ray emissions of this source did not follow the significant changes observed in $\gamma$-rays. As for the NIR and optical emissions, we derived only upper limits for this source that are indeed vary faint, especially in the optical energy bands (Courbin et al. 2002). Nevertheless, by comparing the derived upper limits in the J band (red downward arrow in Figure 2) with the NIR data reported by Courbin et al. 2002 and Meylan et al. 2005, we can exclude variation in the thermal + non-thermal components greater than a factor of ~1.5. The soft and hard X-Ray emissions also exclude variation greater than a factor of 1.6 and 1.5, respectively. It is worth noting that the observed variations of the SED rule out the hypothesis that the $\gamma$-ray emission was connected to microlensing since its effects would be energy independent. On the other hand, the chromaticism of the SED variability may suggest that microlensing from stars in the lensing galaxy may cause the observed $\gamma$-ray variability (see, e.g., Torres et al. 2003). In order to investigate this possibility, we simulated the transition of a source with different dimensions (Jovanović et al. 2008) across the microlensing magnification pattern for the lens system (taking the convergence $k = 0.158$ and shear $\gamma = 0.096$ as given in Winn et al. 2002). By assuming a $\gamma$-ray emitting region of 10$^{15}$ cm (observer frame), we found an amplification by a factor of tens on a timescale of years. Even worse is the case of the $\gamma$-ray flare observed by Fermi on a 6 hr timescale, which is a factor
of 35 higher than the steady state, requiring high amplification in a very short time. Shorter timescales of microlensing can be obtained with a very compact source (on the order of $10^{13}$ cm), but we cannot further reduce the $\gamma$-ray emitting region; otherwise, it would result in an increase in $\gamma$-ray opacity due to pair production. Therefore, we found that the observed variability is more likely intrinsic to this blazar.

We complemented the low-frequency data with the non-simultaneous Planck observations (30, 100, and 217 GHz) taken from the Early Release Compact Source Catalogue (ERSCSC) extracted from the first all-sky survey. In Figure 2 we report all the observed multifrequency data and the SED modeling, taking into account the achronic magnification due to the gravitational lensing, assumed to be of order of magnitude (De Rosa et al. 2005).

We model three $\gamma$-ray states of the source. The first one is the average state reported by De Rosa et al. (2005) and consistent with the average $\gamma$-ray state reported in Abdo et al. (2010; $\sim 40 \times 10^{-8}$ photons cm$^{-2}$ s$^{-1}$; see black points in Figure 2); the second is the one-month enhancement showing a mean flux of $\sim 200 \times 10^{-8}$ photons cm$^{-2}$ s$^{-1}$ (blue points in Figure 2); the third is the peak of the $\gamma$-ray emission (October 14–18; hereafter “flare”), which is a factor of $\sim 2$–3 greater than the one-month average flux (red points in Figure 2). We note that the multifrequency behavior of the source, i.e., the lack of correlated variability between the low (NIR–optical bands, X-Rays) and high ($\gamma$-rays) energy portions of the SEDs, disfavors the one-zone leptonic model for this event. We account for this evidence, assuming two relativistic electron populations with the energy density described by a broken power law in the Lorentz factor domain ($\gamma$) with break equal to $\gamma_b$:

$$n_e(\gamma) = \frac{K \gamma_b^{-1}}{(\gamma/\gamma_b)^{a_1} + (\gamma/\gamma_b)^{a_2}},$$

where $a_1$ and $a_2$ are the pre- and post-break electron distribution spectral indices, respectively. We assume that the two electron populations contained a random magnetic field $B$. In Table 1 we summarize the values of the model parameters for the two components.

We estimate the contributions of both electron populations to synchrotron emission and to synchrotron self-Compton plus inverse Compton from external seed photons (EC) originating in a dusty torus, in the accretion disk, and in the broad-line region (BLR; see Sikora et al. 2002; Vittorini et al. 2009). In particular, we assume (1) the emission from a torus with temperature $T = 10^7$ K and $1.26 \times 10^{19}$ cm from the central engine, (2) the direct emission from the disk with $T = 1.5 \times 10^4$ K and luminosity $L_{\text{disk}} = 6 \times 10^{46}$ erg s$^{-1}$ and $5 \times 10^{16}$ cm from the second population, and (3) the emission from the BLR and $R_{\text{BLR}} = 5 \times 10^{17}$ cm from the central engine and reprocessing 10% of the disk luminosity.

In this scenario, the average $\gamma$-ray state is produced through EC on dusty torus, disk, and BLR seed photons mainly by the first population, resulting in a jet power of $P_{\text{jet}}^1 = 10^{46}$ erg s$^{-1}$ (black line in Figure 2). The one-month $\gamma$-ray enhancement, a factor of four higher than the average flux, has required the additional contribution of the second electron population, which is characterized by a smaller size, higher electron density and higher $\gamma_b$ with respect to the first electron population (Table 1). On the basis of these assumptions, the $\gamma$-ray enhancement (blue points in Figure 2) is then produced by EC of the second population on the photon density field while moving inside the BLR with $\Gamma = 15$, transporting a jet power of $P_{\text{jet}}^2 = 3 \times 10^{46}$ erg s$^{-1}$. This modeling is in agreement with the source fading at its average flux level when the blob is moving outside the BLR ($\Delta t \sim R_{\text{BLR}}(1+z)/c\delta \gtrsim 30$ days). Following this description, the synchrotron and inverse Compton emissions are dominated by the first population, thus accounting for the moderate variation inferred by the NIR–optical and X-Ray observations. On the other hand, the “flare,” which is a factor of 12 greater than the average flux and a factor of $\sim 2$–3 greater than the one-month activity, requires a “local” enhancement of the photon density field by a factor of 3 (red line in Figure 2), likely due to a blob–cloud interaction (Araudo et al. 2010). In this case we derived a jet power of $P_{\text{jet}}^\text{flare} = 6 \times 10^{46}$ erg s$^{-1}$. The lack of correlated variabilities in the optical, X-Rays, and $\gamma$-rays during the flare prevented us from explaining this event as associated with changes in the electron population in terms of injection/acceleration mechanisms.

We emphasize that the $\gamma$-ray behavior of PKS 1830–211 recorded by AGILE and Fermi/LAT between 2010 October and November is rare as probed by the lack of similar variability since 2007. Similarly, no hard X-Ray variability has been noticed by

Table 1

| Population | $\Gamma$ | $B$ (Gauss) | $R$ (cm) | $K$ (cm$^{-3}$) | $\gamma_b$ | $\gamma_{\text{min}}$ | $a_1$ | $a_2$ | $\delta$ |
|------------|---------|-------------|---------|----------------|------------|----------------------|------|------|-------|
| First      | 10      | 0.7         | $8 \times 10^{16}$ | 100           | 100        | 35                   | 2.0  | 2.6  | 16    |
| Second     | 15      | 0.4         | $3 \times 10^{16}$ | 150           | 500        | 60                   | 2.0  | 3.4  | 20    |

Figure 2. Observed SED of PKS 1830–211 for the $\gamma$-ray flare (red filled circles), for the one-month enhancement (blue filled circles), and for the average state (black points). In detail, the black open circles are the non-simultaneous data from radio to hard X-Rays (Pramesh Rao & Subrahmanyan 1998; Courbin et al. 2002; seven-year INTEGRAL survey, respectively). We report as open stars Planck data taken from the ERCSC of the first all-sky survey. The red downward arrows represent the near-IR SMARTS and the INTEGRAL/IBIS (20–40 keV) upper limits. Solid lines represent the SED models for the three $\gamma$-ray states (black for the average (EGRET), blue for the one-month, red for the flare). The models were magnified by a factor of 10 for the lensing.

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17 http://www.sciops.esa.int/index.php?project=planck&page=Planck_Legacy_Archive
observed during seven years of monitoring by INTEGRAL/IBIS. In conclusion, we can attribute the properties of PKS 1830–211 to the ones of “γ-ray only flaring” blazars showing substantial variations, especially in the γ-ray energy range above 10–100 MeV. These evidences strongly support our interpretation of a “steady” electron population, filling the jet below the BLR, that is responsible for the average γ-ray emission recorded by both EGRET and Fermi/LAT more than 10 years apart.

It is worth noting that the inspection of the γ-ray light curve during a longer period across the October–November enhancement did not show any evidence of the time delay between the emissions of the two lensed images A and B as measured in the radio maps (26±4 days; Lovell et al. 1998). We can assume the lack of the delay between A and B only if the flux ratio of the two components is ~1. If it was lower than 1, we are prevented from drawing any conclusions because the emission would have occurred below the AGILE sensitivity level. We also note that microlensing could play a role in explaining the possible lack of echo in the γ-ray light curve. In fact, in some lensed quasars (Blackburne et al. 2006), different flux ratios in the lensed images were detected between the optical and X-Rays. This dependency of the flux ratio on the energy has been interpreted as due to microlensing, thus justifying different amplifications as a function of the emitting region size (see also Jovanović et al. 2008). On the basis of this evidence, we can consider that the lack of the γ-ray echo may be due to different flux ratios between the two components in radio and γ-ray energy bands, i.e., it might be that one component (due to the flux anomaly) has a negligible contribution in γ-rays. Consequently, intrinsic variation in combination with microlensing can also be considered.

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