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OPTICAL AND NEAR INFRARED STUDIES OF γ-RAY BRIGHT *WMAP* SOURCES

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RESUMEN

WMAP ha producido un catálogo de fuentes emisoras de ondas milimétricas fuera del plano Galáctico, las cuales son supuestamente blazares. Comparamos el catálogo de *WMAP* con el tercer catálogo de EGRET y la lista de fuentes brillantes del *Fermi* γ-ray Space Telescope, definiendo una muestra de objetos brillantes en l milimétrico y rayos γ. Presentamos brevemente algunos resultados del estudio exhaustivo de estos objetos empleando instrumentación óptica y en el cercano infrarrojo en el telescopio de 2.1 m del Observatorio Astrofísico Guillermo Haro de Cananea.

ABSTRACT

WMAP has produced a catalog of millimeter-wave sources outside the Galactic plane, assumed to be primarily blazars. We compared the *WMAP* catalog with the third EGRET catalog and the early list of bright sources compiled by the *Fermi* γ-ray Space Telescope, defining a sample of mm-wave/γ-ray bright objects. We briefly present some results from an exhaustive survey of these objects, using optical and near infrared instrumentation at the 2.1 m telescope of the OAGH Cananea observatory.

Key Words: BL Lacertae objects: general — galaxies: active — quasars: general

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1. INTRODUCTION

Radio loud γ-ray emitting quasars are believed to be active galactic nuclei (AGNs) powered by a supermassive black hole accreting vast amounts of matter, part of which is violently ejected in powerful jets oriented towards our line of sight. Although these objects are intrinsically rare, they can be observed at large distances and used to sample the distant universe. The advent of sensitive instruments in the millimeter wave and γ-rays regimes opens the possibility of finding and using high redshift blazars for testing AGN evolution, the growth of supermassive black holes during the early history of the Universe, sampling the extragalactic background light and relate it to the star formation history of the Universe.

2. γ-RAY AND MM-WAVE BRIGHT BLAZARS

Fifteen years have passed since the Energetic γ-Ray Experiment Telescope (EGRET) on board of the *Compton γ-ray Observatory* first demonstrated that active galactic nuclei, in particular blazars, are celestial sources of γ-ray photons (von Montigny et al. 1995). Of the 271 entries in the 3$^{\rm rd}$ EGRET catalog (3EG) of high-energy gamma-ray sources (Hartman et al. 1999), 66 were classified as high confidence blazar detections and 27 as low confidence ones. The correspondence between EGRET sources and flat spectrum radio loud quasars (FSRQs) was formally verified by Mattox et al. (1997) and extended to the 3EG catalog by Mattox, Hartman, & Reimer (2001).

The radio catalogs used by Mattox, Hartman, & Reimer (2001), namely the GB6 and PMN catalogs, cover practically all the sky as observed at 4.8 GHz, containing tens of thousands of radio point sources (Gregory et al. 1996, 1994), most of them AGNs. Radio emission from AGNs is known to extend into the millimeter wave range, been a source of contamination for cosmic microwave background (CMB) experiments. As a by-product, CMB experiments can compile lists of foreground sources in their data, to be excluded in cosmological analysis. The *WMAP* collaboration produced a list of 208 foreground sources from their first year of data (Bennett et al. 2003), which after five years of observations grew into a full catalog of 390 bright sources between 23 and 94 GHz, localized inside a mask covering 88% of the sky, excluding primarily the Galactic plane (Wright et al. 2009).

The *WMAP* catalogued sources are of intrinsic interest for millimeter wave telescopes. Aside from their practical use as bright pointing references, they provide a sample of extragalactic objects up to redshifts $z \lesssim 3$. Even thought some counterparts appear obvious, the use of *WMAP* sources as mm-wave

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pointing references requires a formal identification procedure, as *WMAP* positions are only accurate to 4 arc-minutes. A single large aperture antenna, like the 50 meter Large Millimeter Telescope (LMT; Serrano Pérez-Grovas et al. 2006), can rapidly position objects to arc-second accuracy and confirm or reject presumptive counterparts. LMT can measured fluxes with high signal-to-noise ratio in seconds, providing the data required to assess and study rapid variability in the optically thin regime. In addition to the intrinsic interest in understanding these objects, single dish mm-wave observations of blazars provide the framework to study distant AGNs, observable to arbitrarily large distances. With the ability to reach sub-mJy fluxes within a minute, LMT will have the potential to observe *WMAP* analogs beyond $z \gtrsim 10$ — if something did emit radiation at such early stages of cosmic history.

3. γ-RAY EMISSION AMONG *WMAP* SOURCES

3.1. *Matching the WMAP and 3EG catalogs*

WMAP foreground sources are certainly related to γ-ray blazars. We made a comparison between the 3EG and *WMAP* catalogs, with a relaxed matching criterion of 2.5 times the positional uncertainty, defined by $\sqrt{\theta_{95}^2 + \sigma_{\rm wmap}^2}$, where θ_{95} is the 95% confidence radius defined in 3EG (Hartman et al. 1999) and $\sigma_{\rm wmap} = 4'$ is the *WMAP* positional uncertainty. The comparison produces 69 matches of *WMAP* sources with the 186 3EG sources with $|b| > 10°$. The extending search to $2.5\,\theta_{95}$ leads to an expectation of 8.2 random coincidences and most of the matches are bound to be real. In fact all source types (A, a, u) match above the random expectation rate. Figure 1 shows the positional coincidences as a function of the γ-ray source type, as entered in the 3EG catalog: 43 out of 65 high confidence EGRET blazars identifications are positionally coincident with *WMAP* sources, 13 of them outside the nominal 1σ uncertainty. We note 11 coincidences among the 97 unidentified EGRET sources with $|b| > 10°$, four of them fair ($\leq 1.5\sigma$). There is a 50% increase in the matches when the match criterion is relaxed from 1.0σ to 1.5σ; further increasing the criterion to 2.0σ and 2.5σ gives lower increases in matching rates, more attributable to random coincidences. Still, we kept the larger value preferring the inclusion of random mm-wave AGNs in our sample than the risk of rejecting true γ-ray sources.

We tested and found that the *WMAP* and EGRET fluxes of the selected objects are not well correlated and that the sample covers all the redshift range of the *WMAP* sources.

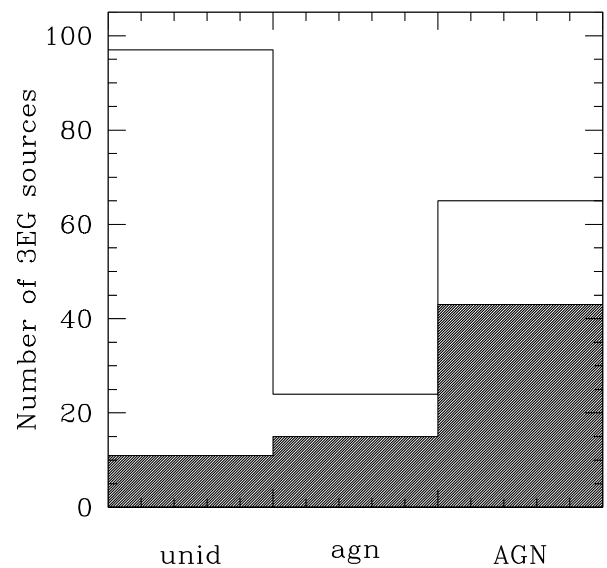

Fig. 1. Coincidences between the *WMAP* and 3EG catalogs. The solid line histogram separates the 186 $|b| > 10°$ 3EG sources in three classes: high confidence EGRET blazar detections (AGN), low confidence ones (agn) and unidentified sources (unid). The shaded histogram indicates *WMAP* coincidences for each class.

3.2. *Matching WMAP sources with VHE photons*

A second exercise consisted in matching *WMAP* sources with the list of $E > 10\,$GeV photons compiled from the EGRET data by Thompson et al. (2005). EGRET detected 1506 such VHE photons as named in Thompson et al. (2005), most from the Galactic plane, with 613 complying with $|b| > 10°$. These might be considered "extragalactic VHE background photons", as only 48 of them are coincident with (30 of the $|b| > 10°$) 3EG sources. The precise level of the extragalactic γ-ray background is uncertain, its determination been highly dependent on properly modeling the Galactic diffuse emission (Sreekumar et al. 1998; Strong, Moskalenko, & Reimer 2004). The uncertainty in the extragalactic background bears on whether unresolved blazars can account for its origin or new types of hard sources are required (Mücke & Pohl 2000; Dermer 2007).

As the EGRET point spread function was narrower at GeVs, VHE photons are better to localize undetected high energy sources. Individual VHE photons have positional uncertainties of 0.5°. We searched for coincident *WMAP* sources and VHE photons. We noted 34 coincidences, close to what is expected by pure chance (32.3). Near coincidences (1σ box) are slightly more common than random: 10 versus 5.2, a 6.3% probability random event.

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3.3. *Matching WMAP with Fermi bright sources*

The *Fermi γ-ray Space Telescope* was put in orbit on June 2008. Its first light map showed a prominent 3C454.3, reminding the transient nature of γ-ray blazars. A list of 205 bright γ-ray sources detected with statistical significance $\gtrsim 10\sigma$ in the first three months of observations, the *Fermi* bright source list (0FGL), was made public in February 2009 by Abdo et al. (2009a). The 0FGL sources were localized with positional accuracies typically in the $4' - 10'$ range. About 30 of them are associated with Galactic neutron star sources, and more than 120 with active galaxies, mostly blazars. The *Fermi*-LAT proved efficient in detecting a larger fraction of high-energy peaked BL Lacs (Abdo et al. 2009b), bridging former TeV results with the view of the GeV sky.

We compared *WMAP* and *Fermi* positions. The improved angular resolution of *Fermi* resulted in only 0.85 spurious coincidences expected, even when using a 2.5σ positional criterion. We found 54 posicional coincidences between *WMAP* and the 0FGL, of which only four correspond with EGRET sources and one with an isolated VHE photon.

4. NIR PHOTOMETRY OF MILLIMETER BRIGHT γ-RAY BLAZARS

On August 2007 we started our current monitoring program using optical and near infrared (NIR) instrumentation at the 2.1 m telescope of the Observatorio Astrofísico Guillermo Haro (OAGH), in Cananea, Sonora, Mexico (lat=+31.052, long=−110.384). NIR observations consist of JHK$_s$ photometry using the CAnanea Near Infrared CAmera (CANICA). Optical photometry has been performed with the Cananea direct camera and the Landessternwärte Faint Object Spectrograph Camera (LFOSC). We have also performed spectroscopy using a Böller & Chivens spectrograph and the LFOSC.

We have performed infrared photometry for at least 50 γ-ray emitting *WMAP* blazars, constructing JHK$_s$ light curves which can be compared with *Fermi* light curves, at least for the *GLAST/Fermi* high priority list of targets, whose γ-ray daily and weekly fluxes are available online.

4.1. *3C 454.3*

WMAP J2254+1608 is a bright millimeter source ($F_{\rm 94GHz} = 7.2 \pm 0.4$ Jy), flagged as variable in the *WMAP* catalog. It is positionally coincident with 3EG J2254+1601, one of the best localized EGRET sources. This was later detected as a bright source by *Fermi*, and listed as 0FGL J2254.0+1609. The *WMAP* and *Fermi* best positions are almost identical, with 3C 454.3, a FSRQ at $z = 0.859$, been the obvious candidate counterpart. We started observing 3C 454.3 in October–November 2007, eight months before the *GLAST/Fermi* launch. At that time its flux in the H band was close to 10 mJy. By April 2008 it had increased more than a factor of 3, on time for a bright early γ-ray detection by *Fermi*, shown in the common H and 1–300 GeV light curves in Figure 2. The graph shows a good correlation between the H band and *Fermi* data, as we observed a joint decrease in the flux by a factor of six during the second half of 2008, confirming the physical association of 3C 454.3 with 0FGL J2254.0+1609.

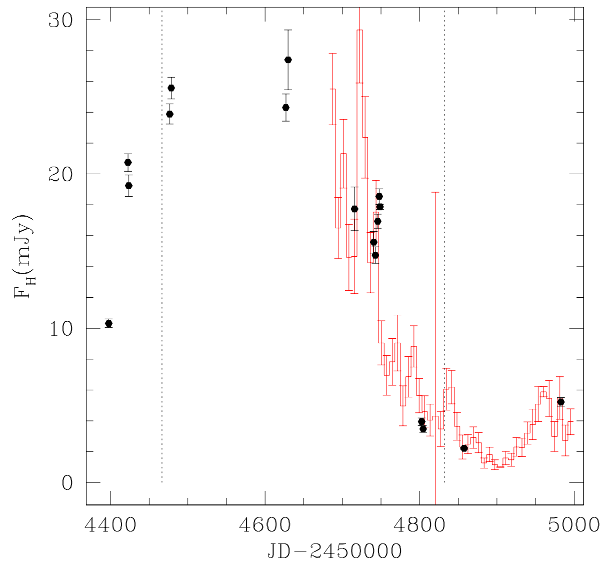

Fig. 2. H band and *Fermi* light curves of 3C 454.3. Vertical dotted lines indicate the beginning of 2008 and 2009. The dots are the CANICA data and the histogram represents the (1–300) GeV weekly flux measured by *Fermi*, with its error bars.

4.2. *AO 0235+164*

WMAP J0238+1637 is also a bright ($F_{94GHz} = 2.1 \pm 0.4$Jy) and variable millimeter source. It is coincident with 3EG J0237+1635 and the *Fermi* bright source 0FGL J0238.6+1636. The compact radio source QSO B0235+164, at $z = 0.940$ is the obvious counterpart. Intervening line absorbers of this QSO are found at $z = 0.852$ and $z = 0.524$.

Our NIR data shows AO 0235+164 rather faint, fainter than the 2MASS reference fluxes, and quiet around the end of 2007 and beginning of 2008. Seven months later, just a few weeks after the *GLAST/Fermi* launch, we found a much brighter infrared source. *Fermi* observed a strong γ-ray flare lasting around 3 months from its onset, coincident with the CANICA H band data, which seems to peak

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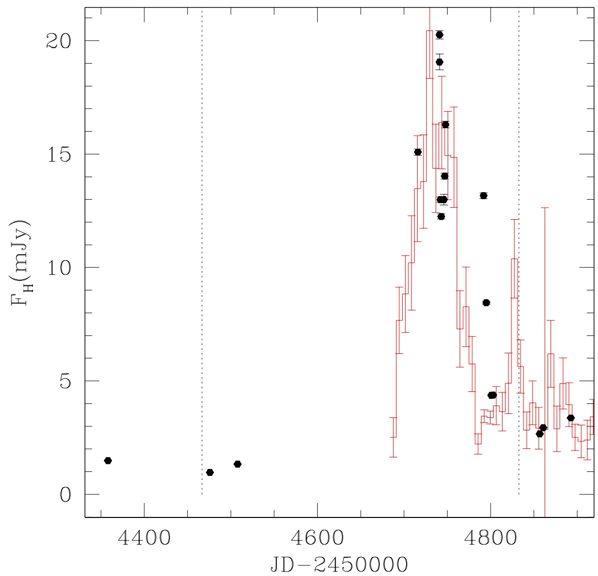

Fig. 3. H band and *Fermi* light curves of AO 0235+164. Vertical dotted lines indicate the beginning of 2008 and 2009. The dots are the CANICA data and the histogram the (1–300) GeV weekly *Fermi* fluxes.

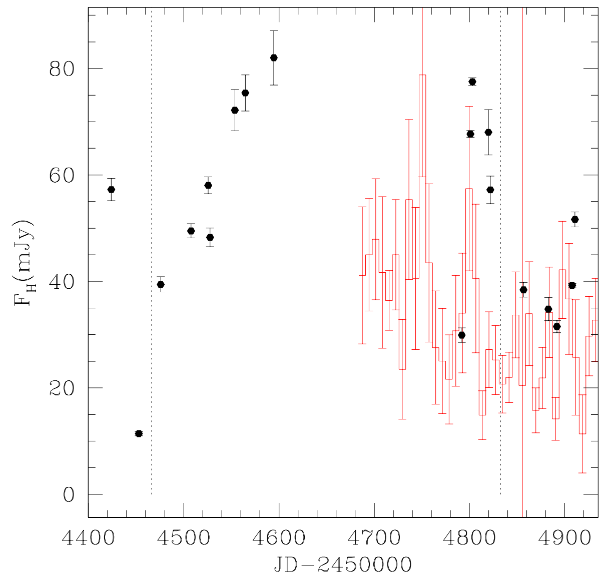

Fig. 4. H and *Fermi* light curves of PKS 0716+714. Vertical dotted lines indicate the beginning of 2008 and 2009. The dots are the CANICA data and the histogram the (1–300) GeV *Fermi* weekly fluxes.

and decrease somewhat later than the GeV emission; both are show in the composite light curve in Figure 3.

4.3. *PKS 0716+714*

The *WMAP* source WMAP J0721+7122 is a positional match to 3EG J0721+7120, also coincident with the *Fermi* bright source 0FGL J0722.0+7120. The *WMAP* and 0FGL error circles are very similar. The radio PKS source is identified with the BL Lac QSO B0716+714, with a redshift $z = 0.3$.

PKS 0716+714 displayed a flux increase in the H band of a factor of 8 during the first four months of 2008, just prior to the *GLAST*/*Fermi* launch. This BL Lac is highly variable in scales of less than a month, as illustrated by the rapid flare around JD2544800, where the H band flux increased by a factor of 3 in ten days and decreased in a similar time. The flare is also seen in the *Fermi* data, as shown in Figure 4. Although the blazar shows rapid and common variability in the NIR and GeV γ-rays, the H band/γ-ray correlation is not as clear as in the previous two examples.

5. THE γ-RAY BLAZAR QSO B0133+47

Our interest in WMAP J0137+4753, formerly WMAP 080 (Bennett et al. 2003), arose from its proximity with the photon VHE 1379, which may well be purely coincidental. This is a bright millimeter source with a mean flux of 1.8 ± 0.2 mJy in the 94 GHz band, flagged as variable by Wright et al. (2009). The *WMAP* best position is consistent with QSO B0133+47, also known as DA 55, a quasar at a redshift $z = 0.859$. This object increased dramatically in brightness from optical magnitude ~ 18 in the 1953–1992 period to $m \lesssim 15$ by 2007, as reported by Yoshida et al. (2008).

EGRET registered the high energy photon VHE 1379 at 22:54:53 UT on 27/9/1996. This photon, unassociated with any EGRET source, has a notorious large energy, $E_\gamma = 85(\pm 38)$ GeV. Its association with the *WMAP* and *Fermi* source is tentative at best, as the angular distance to either is about $1.26° \approx 2.5$ times the photon positional uncertainty (Thompson et al. 2005).

We started monitoring QSO B0133+47 at around the time of the *Fermi* launch. We found it at J=13.3, 2 magnitudes brighter than the 2MASS reference values measured in 1999. Our report of the infrared activity (Carramiñana et al. 2008) was followed four days later by a detection report by *Fermi* (Takahashi & Tosti 2008). It was listed as the *Fermi* bright source 0FGL J0137.1+4751, and flagged as variable. We note that its $E > 100$MeV flux of $10^{-7}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ is close to the EGRET detection limit for that region of the sky. A comparison of optical/NIR and γ-ray fluxes awaits the release of the *Fermi* data.

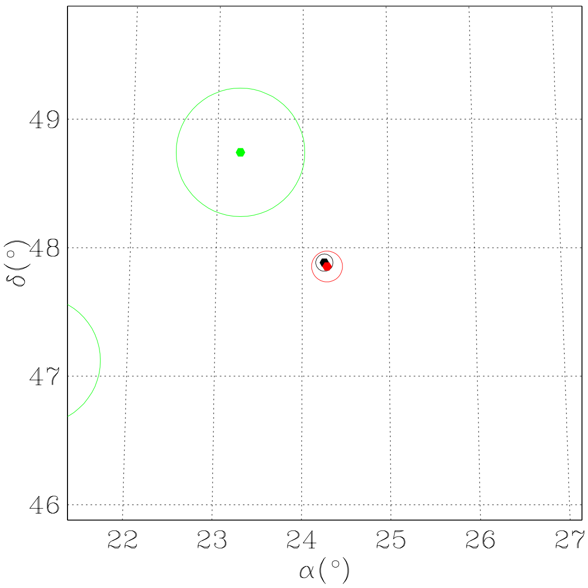

Fig. 5. Location of the VHE 1379 photon (large circle up and left) relative to the *Fermi* and *WMAP* error boxes, indicated by the larger and smaller concentric circles in the center. The grid is in celestial coordinates.

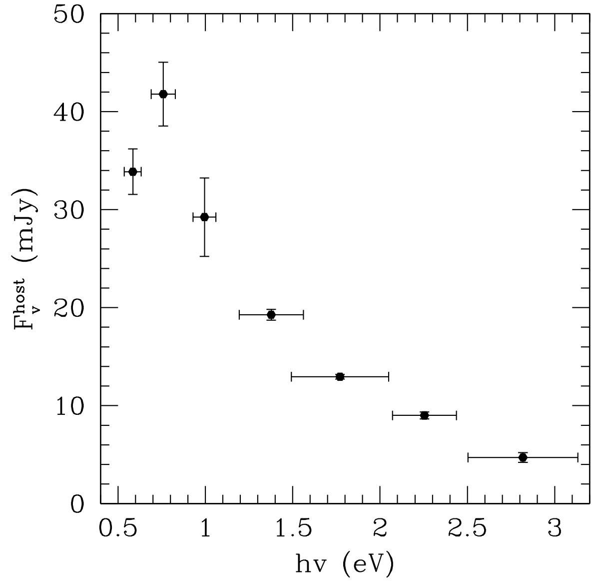

Fig. 6. Spectrum of the Mrk 501 host galaxy, given by the values a, as function of photon energy.

6. OPTICAL AND NIR OBSERVATIONS OF MRK 501

An important surprise during the EGRET era was the non confirmation of most of the newly discovered γ-ray blazars at TeV energies in observations performed with ground based Čerenkov telescopes.The notable exception was Mrk 421, the nearest EGRET blazar. The non detection of more distant blazars led to the paradigm high energy photon absorption by the intervening extragalactic background light (EBL) and the first γ-ray based indirect estimates of the EBL (Stecker & de Jager 1993).

Despite its non detection by EGRET, Mrk 501 was selected as a target by Čerenkov telescopes at that time due to its similarity with Mrk 421 and low redshift ($z = 0.034$). Its ground based detection by Quinn et al. (1996) proved a remarkable support of the EBL hypothesis. It was naturally chosen as a high priority target for *GLAST* and clearly detected by *Fermi* at about $F(> 0.1\mathrm{GeV}) \approx 3\times10^{-8}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, a flux below the sensitivity of EGRET.

Mrk 501 coincides with the bright *Fermi* source 0FGL J1653.9+3946. The millimeter source WMAP J1654+3939 is some $6'$ south of the 0FGL best position and $7'$ from Mrk 501 itself, i.e. somewhat off position. Still, and pending confirmation with a single dish antenna like the LMT, the nature of the different data leads to conclude that the millimeter and γ-ray emissions are common to this nearby BLLac.

Optical and NIR photometry of Mrk 501 is complicated by its bright and extended host, of integrated flux comparable to that of the central point source. As part of a *Fermi* coordinated multiwavelength campaign three months prior to the *GLAST* launch, we performed two sets of observations of Mrk 501 with the direct (BVRI) camera and CANICA at the 2.1 m telescope of the OAGH. We used these to test potential variability of Mrk 501 after subtraction of the host. The optical data consist of four sets of six almost consecutive images taken with each of the BVRI filters; the infrared data consist of a similar number of JHK$_s$ images taken on different epochs spanning 80 days. We performed aperture photometry for each image, using the same aperture radii in all cases, from an inner $3.2''$ to an outer $14.1''$.

We fitted an exponential surface brightness profile to the aperture fluxes, excluding the central one, with the fitted flux in an annuli of internal and external radii r_1 and r_2 given by

$$F(r_1, r_2) = a\left[\left(1+\frac{r_1}{r_0}\right)e^{-\frac{r_1}{r_0}} - \left(1+\frac{r_2}{r_0}\right)e^{-\frac{r_2}{r_0}}\right]. \tag{1}$$

The value of $a = F(0,\infty)$ represents the integrated flux of the host. The fluxes measured in the rings excluding the central aperture determined the fit parameters a and r_0, with respective errors. We found all $\{a \pm \Delta a, r_0 \pm \Delta r_0\}$ sets consistent with a single value for a given color. The values of a as function of wavelength form the host spectrum shown Figure 6.

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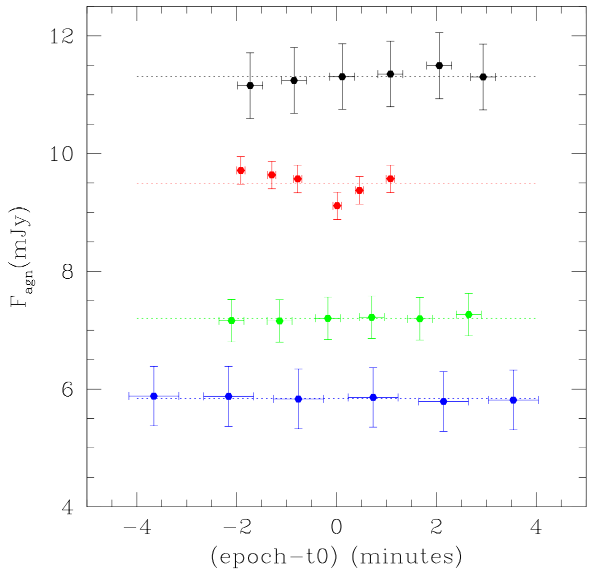

Fig. 7. Host substracted BVRI light curves of Mrk 501. Each color is shown at its actual flux level but relative to a different epoch, t_0. All light curves are consistent with constant flux (horizontal dotted line).

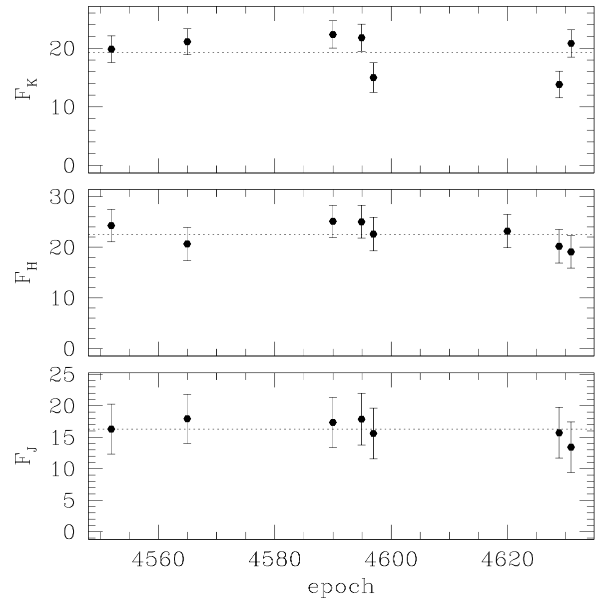

Fig. 8. Host substracted JHK$_s$ light curves of Mrk 501, all consistent with the constant flux indicated by the horizontal dotted line.

We note that the R band magnitude is consistent with previous determinations (Nilsson et al. 2007). The AGN flux was determined subtracting the host flux interpolated to the central aperture.

Figure 7 shows the BVRI light curves, all spanning less than 8 minutes around different epochs: (254)4554.999, 4554.992, 4554.963 and 4554.973 for *BVRI* respectively. A small flux decrease in the R band, of no statistical significance, is noticed; the measurements are consistent with a constant flux.

The NIR light curves are shown in Figure 8. They are consistent with a constant flux, even with the K$_s$ band having a $\chi^2 = 12.78$ for 7 degrees of freedom.

7. SUMMARY

We presented here examples of the studies been performed with the 2.1 m OAGH instruments in an effort to understand the functioning of γ-ray sources. The future entry online of LMT will expand our multiwavelength coverage and allow us to reach much fainter sources, at the same time that the *Fermi* γ-Ray Space Telescope reaches its full potential.

We warmly thank the OAGH staff for its support. We made extensive use of the public facilities in the SIMBAD, 2MASS, POSS/HST and *Fermi* websites.

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