Extensive near infrared monitoring of millimeter-wave / gamma-ray bright blazars

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We established a sample of millimeter-wave and γ-ray bright active galactic nuclei matching the WMAP catalog with the EGRET catalog, highest energy photons and the Fermi bright source list. We have monitored over 80 of these objects in the near infrared, obtaining over 2000 JHKs data points directly comparable with Fermi data. We present examples of correlated near infrared and γ-ray activity of known blazars and recently identified sources.

I. MM-WAVE γ-RAY BRIGHT BLAZARS

CGRO-EGRET established the predominance of flat spectrum radio quasars (FSRQ) as extragalactic sources of high-energy γ-rays [1]. These are believed to be powered by supermassive black holes ejecting large amounts of material along relativistic jets perpendicular to accretion disks and producing high energy particles in these jets. Observations at the highest photon energies shown a predominance of Bl Lac objects over FSRQ at $E \sim 1$ TeV. Although these observations may be biased by the horizon limitation due to pair absorption with extragalactic background light (EBL), the Fermi γ-ray Space Telescope, more sensitive and more responsive to GeV photons than EGRET, reported a larger fraction of Bl Lac objects among blazars in its bright source list release (0FGL) [2, 3]. The wider spectral coverage of Fermi is allowing detailed studies of the intrinsic properties of various types of active galactic nuclei (AGN), cosmic evolution and their use as EBL tracers [4].

The extrapolation of FSRQ to high radio frequencies makes the coincidence of foreground WMAP sources with γ-ray blazars expectable. Furthermore, it is clear than most of the 390 WMAP sources are AGNs [3]. These emitters are dominated in the mm-wave band by the same synchrotron component observed at lower frequencies and can be expected to emit photons of very high energy, related to the hardest part of the synchrotron emission. WMAP sources have fluxes above 0.1 Jy at frequencies $\sim 40$ GHz, making them suitable positional references for large millimeter telescopes. Known common WMAP/EGRET sources, found up to $z \gtrsim 2.3$, are relatively nearby analogs of more distant blazars detectable in principle by Fermi up to $z \gtrsim 7$ and by the Large Millimeter Telescope (LMT [6]) at $z \gtrsim 30$, if such an object could have existed at such an early phase of the Universe. The combination of Fermi and LMT data promises the availability of a sample of thousands of objects up to the highest redshifts ideally suited to study radio loud AGN evolution and the connection of the EBL with the star formation history of the Universe.

II. MATCHING WMAP WITH γ-RAY SOURCES

As a by product of the study of the cosmic microwave background, the Wilkinson Microwave Anisotropy Probe (WMAP) produced a catalog of 390 bright sources detected at frequencies between 23 and 94 GHz, outside a mask defined by the mm-wave emission from the Galactic plane [5]. These objects constitute a fairly homogeneous sample suitable for comparison with all-sky γ-ray catalogs.

TABLE I: WMAP and EGRET source matches by type. (∗ = excludes P, G and S types [1]).

| Source Type | 3EG catalog | WMAP mask | Matches | Expected |
|-------------|-------------|-----------|---------|----------|
| A           | 67          | 54        | 40      | 6.6      |
| a           | 28          | 23        | 17      | 3.3      |
| U           | 170         | 61        | 11      | 10.0     |
| Total       | 265$^*$     | 138       | 68      | 20       |

The positional uncertainty of WMAP equals 4′, similar to that of Fermi, but much better than that of EGRET. Preferring to accept false positives than to reject real coincidences, we used a relaxed matching criterion of 2.5 times the combined positional accuracy, $(\sigma_W^2 + \sigma_\gamma^2)^{1/2}$, where $\sigma_\gamma$ refers to 3EG (∼ 1′), EGRET-VHE (0.5′) or 0FGL (2 – 10′). For each comparison we estimated the expected number of random coincidences quantifying the solid angle covered by the γ-ray sources (or events) outside the WMAP Galactic mask. For each WMAP/γ pair we blindly listed potential radio, optical and X-ray counterparts from SIMBAD / Vizier. The results are listed in tables II and III.
### TABLE II: em WMAP sources in the 3EG catalog and 0FGL bright source list – Part I.

*D* denotes the integer part of the distance in standard deviations.

| WMAP    | 3EG / 0FGL                  | D   | Counterpart     | WMAP    | 3EG / 0FGL                  | D   | Counterpart     |
|---------|-----------------------------|-----|-----------------|---------|-----------------------------|-----|-----------------|
| J0050–0649 | 0FGL J0051.1–0647          | 0   | PKS 0048–071    | J0334–4007 | 0FGL J0334.1–0406         | 0   | PKS 0332–403    |
| J0051–0927 | 0FGL J0050.5–0928          | 0   | PKS 0048–097    | J0339–0143 | 3EG J0340–0201            | 0   | CTA 026        |
| J0108+0135   | 3EG J0118+0248             | 2   | 4C 01.02        | J0407–3825 | 0FGL J0407.6–3829         | 0   | PKS 0405–385    |
| J0132–1563   | 3EG J0130–1758             | 1   | QSO B0130–171   | J0416–2051 | 3EG J0412–1853           | 1   | (QSO B0413–21)? |
| J0137+4753   | 0FGL J0137.1+4751          | 0   | QSO B0133+47    | J0423–0120 | 0FGL J0423.1–0112         | 0   | QSO B0420–015   |
| J0204+1513   | 3EG J0204+1458             | 0   | 4C +15.05       | J0428–3757 | 0FGL J0428.7–3755         | 0   | PKS 0426–380    |
| J0205–1704   | 0FGL J0204.8–1704          | 0   | PKS 0202–17     | J0442–0017 | 3EG J0442–0033           | 0   | QSO B0440–004   |
| J0210–5100   | 0FGL J0210.8–5100          | 0   | QSO B0208–5115  | J0455–4617 | 3EG J0458–4635           | 0   | 0454–463        |
| J0218+0138   | 0FGL J0217.8+0146          | 1   | PKS 0215+015    | J0456–2322 | 0FGL J0457.1–2325        | 0   | QSO B0454–234   |
| J0220+3558   | 0FGL J0220.9+3607          | 0   | B2 0218+35      | J0501–0159 | 3EG J0500–0159          | 0   | 4C –02.19       |
| J0223+4303   | 0FGL J0222.6+4302          | 1   | 3C 66A          | J0506–6108 | 3EG J0512–6150          | 1   | 0506–612?       |
| J0327+2848   | 0FGL J0328.4+2855          | 0   | 4C +28.07       | J0523–3627 | 3EG J0530–3626          | 2   | QSO J0522–3627  |
| J0338+1637   | 0FGL J0337.6+1636          | 0   | AO 0235+16      | J0538–4405 | 0FGL J0538.8–4403       | 0   | PKS 0537–441    |
| J0319+4131   | 0FGL J0320.0+4130          | 1   | NGC 1275        | J0539–2844 | 3EG J0531–2940          | 2   | (QSO J0539–2839)? |

**A. Matching WMAP with EGRET**

The comparison between the WMAP and 3EG catalogs produced 69 matches out of the 390 WMAP and 138 EGRET sources outside the WMAP Galactic mask. The number expected randomly is 20; the probability of having 69 matches among the 390 WMAP sources is $P < 10^{-17}$, indicating that most but not all the matches are real.

When accounting for the source type we count 40 matches out of the 54 high confidence blazar association, labelled A in the 3EG catalog, compared to 6.6 expected randomly. The low confidence "a" associations have 17 matches out of 23 tries and 3.3 expected chance coincidences. On the other hand we have 11 matches among the 61 unidentified sources out of the WMAP mask, expecting 10.0 by chance. On statistical grounds, we can confirm the physical association of foreground WMAP sources with 3EG blazars, accounted by both "A" and "a" classes, but not with unidentified EGRET sources (table I).

We also compared the WMAP positions with the list of very high energy (VHE) photons, $E > 10 \text{ GeV}$: 510 out of the 1506 VHE photons are outside the WMAP Galactic mask. The combined positional accuracy of VHE photons and WMAP sources is $30.2^\circ$. We obtained coincidences between 33 VHE photons and 29 WMAP sources as follows:

- 20 WMAP sources coincide with a single isolated VHE photon;
- 4 WMAP sources coincide with a single VHE photon and a 3EG, with no 0FGL counterpart;
- 1 WMAP source (WMAP J1408–0749) coincides with a 3EG source (3EG J1409–0745) and 4 VHE photons (VHE 494, 498, 1058 and 1061) – but with no 0FGL counterpart;
- 3 WMAP sources coincide with VHE photons, 3EG and 0FGL sources; of these WMAP J0210–5100 has two VHE photons;
- 1 WMAP source (WMAP J0137+4753) coincides with a VHE photon and a 0FGL source (0FGL 0137.1+4751), with no 3EG counterpart.

We note that given the number and error box sizes of the VHE photons, we expect 30 random matches under our $2.5\sigma$ criterion. Most or all of the single WMAP-VHE coincidences are likely to be spurious. We note the case of WMAP J0137+4753, which belonged to the WMAP & VHE only category prior to the publication of the 0FGL and turned out to be a real $\gamma$-ray source.
B. Matching the WMAP bright source list

The Fermi bright source list (0FGL), made public in February 2009, consists of 205 bright $\gamma$-ray sources detected with significance $\sqrt{TS} > 10$ in the first three months of observations [2]. Of these, 121 are of the AGN class, mostly blazars [3]. The 0FGL list has 122 objects outside the WMAP Galactic mask, which we compared with the respective WMAP and Fermi positions. The improved positional accuracy of Fermi, in the $4' - 10'$ range, results in only 0.82 spurious coincidences expected. We found 54 matches between WMAP and the 0FGL, 25 of which are common with EGRET sources and 29 are independent.

C. Sample overview

The sample is presented in tables II and III. The $D$ column expresses the distance between the WMAP and the $\gamma$-ray event in terms of the integer part of the combined positional accuracy; associations with [0] have intersecting error contours and are more likely to be real than those with [2], separated by $\geq 2\sigma$. Most of the sources have a suitable radio, optical and/or X-ray counterpart, often in the intersection of the WMAP/$\gamma$-ray error boxes. In a few cases the candidate counterpart is not unique and the one displayed is a subjective election. Counterparts in parenthesis are tentative. We note the following:

- WMAP J0051–0927 :: 0FGL J0050.5–0928 has a preferred association with the Bl Lac object PKS 0048–071 = PHL 856; the radiogalaxy FIRST J005051.9–092529 is an alternative.
- WMAP J0237+2848 :: 0FGL J0238.4+2855 :: 3EG J0239+2815. This is listed as a low confidence Fermi association with 4C $+28.07$ in [2]. The WMAP and Fermi boxes match, both containing 4C $+28.07$. All are somewhat outside the EGRET box.
- WMAP J0319+4131 :: 0FGL J0320.0+4131 is identified with the radiogalaxy Cen A is excluded from this study by the WMAP Galactic mask.
- WMAP J0423–0120 :: 0FGL J0423.1–0112 :: 3EG J0422–0102. This is a low confidence Fermi association with PKS 0420–014, which is at the center of the WMAP circle.
- WMAP J0909+0119 :: 0FGL J0909.7+0145. The 0FGL error radius is $17'$, the WMAP and 0FGL positions differing by $25'$. PKS 0907+022 is a low confidence Fermi association not compatible with WMAP. 4C $+01.24$ (PKS = QSO B0906+015) is inside the WMAP box and marginally compatible with the Fermi source.
- WMAP J1517–2421 has two possible EGRET counterparts but only one (3EG J1517–2538) is compatible with the 0FGL source.
- WMAP J1642+3948 is 19 $''$ away from 0FGL J1641.4+3939, which has a positional error of 9.5 $''$, making the association tentative. There are suitable candidates for both sources, with 3C345 being positionally the best common counterpart, as discussed in [VC]. While there is no 3EG source association, we note the revised EGRET counterpart EGR J1642+3940 [5].

III. NEAR INFRARED MONITORING

On August 2007, we started a dedicated monitoring program with up to 60 nights per semester awarded on the 2.1m telescope of the Observatorio Astrofísico Guillermo Haro (OAGH), in Cananea, Sonora, Mexico (lat=$+31.05$, long=$-110.38$). The program consists of optical photometry (BRVI), low resolution spectroscopy (4000 - 7500 $\AA$) and near infrared JHKs imaging of the sample above, with the addition of high priority GLAST/Fermi sources and targets notified via the multi-wavelength Fermi group. The current study is to lead to programs of follow-up and identification of $\gamma$-ray sources using near infrared, optical and mm-wave facilities.

Particularly successful has been the JHKs photometric survey using the CANanea Near Infrared Camera (CANICA). CANICA is equipped with a Rockwell 1024 x 1024 pixel Hawaii infrared detector working at 75.4 K with standard near infrared filters. The scale plate is 0.32 $''$/pixel. Observations are usually carried out in series of dithered frames in each filter. Datasets are coadded after correcting for bias and flat-fielding using IRAF based macros. Figure [1] shows the photometric magnitudes measured with CANICA, with detection thresholds around magnitudes 19, 18 and 17 for J, H and Ks respectively, i.e. about two magnitudes fainter than 2MASS.

IV. CORRELATED INFRARED/$\gamma$-RAY ACTIVITY

We have found correlated infrared and $\gamma$-ray correlations with little or no evidence for time delays in our sample. We show here joint CANICA H band (1.6 $\mu$m $\Rightarrow$ 0.76eV) and Fermi (1 – 300 GeV) light curves, normalizing the maximum $\gamma$-ray flux to the maximum H-band flux and setting both zeros at the same level. We are currently studying the infrared
PKS 0235+164 is positionally coincident with WMAP J0238+1637, mm-wave source coincident with 3EG J0237+1635 = 0FGL J0238.6+1636. The WMAP source is labelled as probable variable. Figure 2 shows the joint H band and 1-300 GeV fluxes scaled. The near infrared flux at the end of 2008 and beginning of 2009 matched the 2MASS values. On JD2454715 we found PKS 0235+164 almost three magnitudes brighter, prior to peaking 25 days later - in coincidence with the Fermi flare.

C. PKS 1510–089

PKS 1510–89 is the high confidence counterpart of 3EG J1512–0849, WMAP J1512–0904 and 0FGL J1512.7–0905, with an excellent positional match between all data. We started monitoring PKS 1510–89 in early 2008, a few months prior to the Fermi launch, when the flux fluctuated around the 2MASS reference value. We caught a simultaneous infrared - γ-ray flare on JD 2454924 and the subsequent decay a month later.

V. SOURCE IDENTIFICATIONS

A. The identification of QSO B0133+476

QSO B0133+476 is a rather active quasar first catalogued originally as DA55 in the Dominion DA 1420 MHz survey [10]. Also known as Mis V1436, archival optical data exists since at least 1953, when it was around magnitude R=18.7. This object has been monitored by other groups since 2007, when it was found to be 4.5 magnitudes brighter. Its optical variability is well documented in [11].

This object has no EGRET counterpart, the only evidence for γ-ray emission prior to the Fermi launch
being its marginal closeness to a \(85(\pm 38)\text{GeV}\) photon. The unprovable association of this single photon with QSO B0133+476 is of interest as its energy is close to the pair absorption EBL limit for the redshift of the object, \(z = 0.859\). If true, this association would indicate the potential of this source for testing the EBL horizon using Fermi, specially under phases of high emission activity. Our report of near infrared flaring from data taken between JD 2454788 and 2454795 \([12]\) was followed by the Fermi detection report, at a flux level above the EGRET limiting sensitivity \([13]\). The infrared light curve is shown in figure 6. The object was caught undergoing a rapid flare which has declined relatively slowly during 2009, but always at levels above 2MASS.
FIG. 7: CANICA - Fermi QSO J0808–0751 light curve. The dots indicate the H band fluxes in mJy, while the histogram and upper limit arrows indicate the 1-300 GeV fluxes and limits in scaled units. The discontinuous horizontal line marks the 2MASS flux. The dotted vertical lines indicate the change of year.

B. QSO J0808–0751

The EGRET source 3EG J0812–0646 was not in the high priority GLAST/Fermi list, with the association with QSO J0808–0751 been only tentative \( (D = 2) \). WMAP J0808–0750 is somewhat displaced from the 3EG location, but contains this \( z = 1.84 \) QSO. The rapid flare observed simultaneously in the near infrared and by Fermi of this source, not in the 0FGL, confirms the identity of the QSO as the \( \gamma \)-ray source. We missed a second flare occurring while the source was on the daylight. The flux increase in the near infrared reached a factor of ten within 50 days.

C. The identification of 0FGL J1641.4+3939 with 3C 345

The angular distance between WMAP J1642+3948 and 0FGL J1641.4+3939 is \( 19.2' = 1.9\sigma \) times the combined positional uncertainty, the association between both objects being tentative only. This is a rather populated region of the sky, where several potential counterparts can be found for each object: - candidate counterparts of 0FGL J1641.4+3939 include 3C 345, QSO B1641.5+3956, QSO B1641.6+3949, QSO B1640+3956, QSO B1640+3944, QSO B1640+396, three more QSOs, a Seyfert 1 and a radiogalaxy from SDSS.

FIG. 8: Left: position of 0FGL J1641.4+3939 (larger circle) and WMAP J1642+3948 (smaller circle) with a few potential counterparts (AGN class - open hexagons). Right: CANICA H band light curve of 3C345 compared with the (1-300 GeV) fluxes from 0FGL J1641.4+3939 by Fermi. The discontinuous horizontal lines mark the 2MASS flux and error. The dotted vertical line indicates the change of year.

VI. SUMMARY

We have selected a sample of mm-wave/\( \gamma \)-ray bright blazars from the WMAP, 3EG catalogs and 0FGL list. We have monitored these in the near infrared finding correlated variability, which has also allowed the identification or confirmation of some of these objects.

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| WMAP    | 3EG / 0FGL | D | Counterpart      | WMAP    | 3EG / 0FGL | D | Counterpart      |
|---------|------------|---|-----------------|---------|------------|---|-----------------|
| J0720-6222 | 3EG J0702-6212 | [2] | ...            | J1510-0546 | 0FGL J1511-2-0536 | [0] | PKS 1508-05    |
| J0721+7122 | 0FGL J0722.0+7120 | [0] | PKS 0716+714  | J1512-0904 | 0FGL J1512.7-0905 | [0] | QSO B1510-089 |
| J0738+1743 | 0FGL J0738.2+1738 | [0] | QSO B0735+178 | J1517-2421 | 0FGL J1517.9-2423 | [0] | QSO B1514-241 |
| J0738+1743 | 3EG J0737+1721 | [0] | ...            | J1517-2421 | 0FGL J1517.9-2423 | [0] | QSO B1514-241 |
| J0808-0750 | 3EG J0812-0646 | [2] | QSO J0808-0751 | J1608+1027 | 3EG J1608+1055 | [0] | 4C +10.45  |
| J0813+4817 | 3EG J0808+4844 | [1] | (4C+48.22)     | J1613+3412 | 3EG J1614+3424 | [1] | QSO B1611+343 |
| J0825+0311 | 3EG J0826+0508 | [0] | QSO B0823+033 | J1624+3948 | 0FGL J1641.4+3939 | [1] | (4C+39.48)  |
| J0831+2411 | 3EG J0829+2413 | [0] | QSO J0830+2411 | J1654+3939 | 0FGL J1653.9+3946 | [1] | Mrk 501     |
| J0841+7053 | 3EG J0845+7049 | [0] | 0836+710       | J1703-6214 | 3EG J1659-6251 | [1] | ...           |
| J0854+2006 | 0FGL J0855.4+2009 | [0] | OJ 287         | J1736-7934 | 3EG J1720-7820 | [2] | ...           |
| J0909+0119 | 0FGL J0909.7+0145 | [1] | PKS 0907+022   | J1740+5212 | 3EG J1738+5203 | [0] | QSO B1739+522 |
| J0920+4441 | 0FGL J0921.2+4437 | [3] | RGB J0920+446  | J1800+7827 | 0FGL J1802.2+7827 | [0] | S5 1803+78    |
| J0957+5527 | 0FGL J0957.6+5522 | [0] | 4C +55.17     | J1820-6343 | 3EG J1813-6419 | [1] | ...           |
| J0959+6530 | 3EG J0958+6533 | [0] | QSO B0954+65  | J1848+3223 | 0FGL J1847.8+3223 | [0] | TXS 1846+3227 |
| J1058–0134 | 0FGL J1057.8–0138 | [0] | PKS 1055+018  | J1849+6705 | 0FGL J1849.4+6706 | [0] | S4 1849+67    |
| J1059–8003 | 0FGL J1100.2–8000 | [0] | PKS 1057–79   | J1923–2105 | 0FGL J1923.3–2101 | [0] | PMN J1923–2104 |
| J1130–1451 | 0FGL J1129.8–1443 | [0] | PKS 1127–14    | J1937–3957 | 3EG J1935–4022 | [2] | ...           |
| J1147–3811 | 0FGL J1146.7–3808 | [3] | 3EG J1134–1530 | J1939–1525 | 3EG J1937–1529 | [0] | QSO B1939–155 |
| J1159+2915 | 0FGL J1159.2+2912 | [0] | 4C +29.45     | J2011–1547 | 3EG J2020–1545 | [2] | QSO B2008–159 |
| J1223–8306 | 3EG J1219–8330 | [1] | ...            | J2035+1055 | 3EG J2036+1132 | [1] | QSO B2032–107 |
| J1229+0203 | 0FGL J1229.1+0202 | [0] | 3C 273         | J2056–4716 | 0FGL J2056.1–4715 | [0] | PMN J2056–4714 |
| J1246–2547 | 0FGL J1246.6–2544 | [0] | PKS 1244–255  | J2143+1741 | 0FGL J2143.2+1741 | [0] | OX 169      |
| J1256–0547 | 0FGL J1256.1–0547 | [3] | 3EG J1255–0549 | J2151–3027 | 3EG J2158–3023 | [2] | PKS 2155–304 |
| J1310+3222 | 0FGL J1310.6+3220 | [1] | B2 1308+32    | J2202+4217 | 0FGL J2202.4+4217 | [0] | Bl Lac     |
| J1316–3337 | 3EG J1314–3337 | [1] | QSO B1313–333 | J2203+1723 | 0FGL J2203.2+1731 | [0] | PKS 2201+171 |
| J1327+2213 | (3EG J1323+2200)? | [2] | QSO B1324+224 | J2207–5348 | 0FGL J2207.0–5347 | [0] | PKS 2204–54 |
| J1337–1257 | 3EG J1339–1419 | [1] | QSO B1335–127 | J2211+2352 | 3EG J2209+2401 | [0] | QSO B2209+236 |
| J1354–1041 | 0FGL J1355.0–1044 | [0] | PKS 1352–104  | J2229–0833 | 0FGL J2229.8–0829 | [0] | QSO B2227–088 |
| J1408–0749 | 3EG J1409–0745 | [0] | QSO B1406–074 | J2232+1144 | 0FGL J2232.4+1141 | [0] | CTA 102    |
| J1419–3822 | 3EG J1424–3734 | [1] | QSO B1417–385 | J2254+1608 | 0FGL J2254.0+1609 | [0] | 3C 454.3   |
| J1427–4206 | 3EG J1429–4217 | [0] | QSO B1424–418 | J2322+4448 | 0FGL J2314.4+426 | [2] | GB6 B2319+4429 |
| J1457–3536 | 0FGL J1457.6–3538 | [3] | 3EG J1500–3509 | J2327+0937 | 0FGL J2327.3+0947 | [0] | GB6 B2325+0923 |
| J1504+1030 | 0FGL J1504.4+1030 | [0] | PKS 1502+106  | J2349+3846 | 3EG J2352+3752 | [1] | QSO B2346+385 |
| J1506–1644 | 3EG J1504–1537 | [1] | (QSO B1504–1626) | J2354+4550 | 3EG J2358+4604 | [1] | 4C 45.51   |