2FHL: The Second Catalog of Hard Fermi-LAT Sources

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on behalf of the Fermi-LAT Collaboration

TeVPA 2015, October 26 – 30, Kashiwa
**Fermi-LAT Catalogs**

*FGL* Catalogs detect and characterize sources in the ~0.1-100 GeV energy range

*FHL* Catalogs explore the higher-energy sky

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Why *2FHL*? Improvement delivered by Pass 8 enables study of the EBL, EGB, Galactic plane, etc, and connects well to the TeV world

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**Acceptance**

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**R$_{68}$ Containment**
80 months of P8 data (50 GeV – 2 TeV)

- 61,000 photons $E > 50$ GeV
- 22,100 photons $E > 100$ GeV
- 2,000 photons $E > 500$ GeV

$\sim 1.5$ photon every deg$^2$
80 months of P8 data (50 GeV – 2 TeV)

61,000 photons E > 50 GeV
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~1.5 photon every deg$^2$
Analysis Details

- **Analysis details**
  - 50 GeV – 2 TeV
  - 80 months of data (till April 2015)
  - Pass 8 (source)
  - Unbinned likelihood

- **Detections**
  - 360 sources:
    - 75% blazars, 11% Galactic sources, 14% unassociated
  - 78 detected by IACTs (TeVCat)
  - 230 detected in 1FHL
  - 303 detected in 3FGL
  - 57 brand new sources (not 1FHL/3FGL)

**Bottom line:** plenty of sources for TeV telescopes
Associations

Preliminary

+ SNRs and PWNe  ◆ BL Lacs  ○ Unc. Blazars  △ Unassociated
  × Pulsars        ◈ FSRQs    △ Others    ○ Extended
Galactic sources have much harder spectra than extragalactic ones
- Median spectral index $\Gamma=2$ vs $\Gamma=3$
- The EBL might be the culprit
- Spectral index can be used to distinguish Galactic objects among the unassociated sources
Spectral Energy Distributions

2FHL J0617.2+2234e (IC 443)

2FHL J1419.3-6047e (PSR J1420-6048)

2FHL J1104.4+3812 (Mkn 421, $z = 0.031$)

2FHL J0222.6+4301 (3C 66A, $z = 0.444$)
Galactic Sources

- **103 sources at \(|b|<10^\circ\)**
  - 42 blazars, 39 Galactic objects, 13 unassociated and 9 Dark Acc.
  - PWNe/SNRs represent 87% of the Galactic population
  - Half of the unassociated sources are hard and thus (likely) Galactic
We used the extended templates of previously detected sources:
- 25 from 3FGL + W41
- Of them 6 sources were not significantly detected:
  - SMC, S 147, Cen-A (lobes), W 44, HB 21, Cygnus loop

Blind search for new sources:
- 72 ROIs of 10°, devoid of sources, centered at $b=0$
- Iteratively add disk source at most significant TS peak
- Fit and choose extended source if $TS_{\text{ext}}>16$

It resulted in the detection of 5 new extended sources
New Extended Sources

- All new sources are significantly detected in 2FHL (TS>75)
- They are hard, and harder than the Galactic diffuse emission
- They are associated to known (3) PWNe and (2) SNRs
- Detailed characterization will be reported in future papers

<table>
<thead>
<tr>
<th>2FHL Name</th>
<th>$l$ [deg]</th>
<th>$b$ [deg]</th>
<th>TS</th>
<th>$TS_{ext}$</th>
<th>$TS_{pts}$</th>
<th>$F_{50}$</th>
<th>$\Delta F_{50}$</th>
<th>$\Gamma$</th>
<th>$\Delta \Gamma$</th>
<th>Association</th>
<th>Class</th>
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<tbody>
<tr>
<td>J0431.2+5553e</td>
<td>150.384</td>
<td>5.216</td>
<td>87.9</td>
<td>83.4</td>
<td>26.2</td>
<td>11.70</td>
<td>2.11</td>
<td>1.66</td>
<td>0.20</td>
<td>G 150.3+4.5</td>
<td>snr</td>
<td>1.27</td>
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<td>-0.388</td>
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<tr>
<td>J1355.2-6430e</td>
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New SNR (G150.3+4.5) discovered by Gao & Han 2014

Preliminary
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Comparison with the H.E.S.S. G.P. Survey

Significance Map

Aharonian et al. 2006, Carrigan et al. 2013

Fermi-LAT >50 GeV Count Map (adaptively smoothed)
**Comparison with the H.E.S.S. G.P. Survey**

H.E.S.S. reported the detection of 69 sources reaching a sensitivity of ~2% of the >1 TeV Crab Nebula flux.

- The LAT detects (in 2FHL) 36 sources in the same region reaching an average sensitivity of 3-4% of the Crab Nebula flux.

- The LAT detects an equal number of PWNe/SNRs while for H.E.S.S they are in a 1.5:1 ratio.

- Within the H.E.S.S. footprint there are:
  - 7 unassociated sources
  - 6 objects coincident with dark accelerators

Aharonian et al. 2006, Carrigan et al. 2013
Example of a dark accelerator

Aharonian+08

Giacani et al. 2011

HESS J1702-420

ATCA-VLA/1.4GHz

Preliminary

$2FHL$
Blazars

Blazar-like objects constitute >80% of the 2FHL Catalog
- Detected up to $z \approx 2$
- Most of them are BL Lacs, only 10 FSRQs
- Different population than 3FGL
SED Peaks

- Being sensitive over ~4 decades in energy, the LAT resolves the high-energy peak
  - Sources become softer at higher energies

![Photon index distribution of BL Lacs](image-url)
Evidence for strong softening of the 2FHL spectra with redshift
- Most likely due to EBL

Several photons detected beyond the horizon
- Very important to constrain the EBL
Measuring the intrinsic spectral index: fitting an EBL-absorbed power law model to 128 2FHL blazars with a redshift. The intrinsic spectra are much harder than the observed ones.

Spectral breaks between the VHE and Fermi band have been used as diagnostic for/against the EBL (Essey & Kusenko, Sanchez+13, etc). Spectral flattening at high redshift has been interpreted as sign of interesting physics.
Dependence of spectral breaks between the 2FHL and 3FGL bands with redshift can be explained as produced by the EBL alone.

There is no evolution of the physics that drives the photon emission in HSP blazars => excellent probes of the EBL.

Simulations of SSC spectra absorbed by the EBL

Simulations of SSC spectra

Domínguez & Ajello 15
Models predict that the >50 GeV EGB is produced by blazars.
Perform simulations of the > 50 GeV sky to determine the detection efficiency
i.e. the probability to detect a source in 2FHL as a function of flux

Di Mauro & Ajello
on behalf of the Fermi/LAT collaboration

Observed Flux distribution

Preliminary

N(>S) ~ S^{-1.5}

CTA flux limit

Preliminary
Summary

- 2FHL opens a new window on the high-energy sky
  - 360 sources detected between 50 GeV and 2 TeV
    - 75% blazars, 14% Galactic and 11% unassociated
    - only 25% detected in TeVCat

- **Galactic science:**
  - all display hard spectra
  - 5 new extended sources, 9 dark accelerators, 87% of PWNe/SNRs
  - good match to the H.E.S.S. Galactic plane survey

- **Extragalactic science:**
  - >80% of 2FHL sources are blazars (BL Lacs), detected up to z~2
  - Clear signs of EBL attenuation (and nothing else)
  - HSP blazars are excellent probes of the EBL
  - Almost all the IGRB is accounted for by blazars
Backup
Detection Pipeline

Seed finding (cell sliding + pgwave)

Extended templates from 3FGL

New Extended Source (pointlike)

Maximum Likelihood Fits

Source-by-source fit to find starting parameters

Global fit #1 (TS<10 sources are dropped)

Global fit #2 (TS<10 sources are dropped)

Generate products for TS>25 and $N_{\text{pred}} \geq 3$ sources

Maximum Likelihood Fits

Position Refinement (gtfindsrc)

NB: all source spectra are modeled as simple power laws
Difficult to study variability with few photons
Yet, 7 sources (all blazars) are found to be variable
Analysis
- 50 GeV – 2 TeV
- ~74 months of data
- Pass 8 (source)
- Unbinned likelihood

Detections
- ~350 sources
- 84 detected by ACTs (TeVCat)
- 238 detected in 1FHL
- 234 detected in 3FGL
- ~60 brand new sources

Analysis
- 50 GeV – 2 TeV
- ~74 months of data
- Pass 7 (source)

Detections in P7
- 227 sources
- Main difference is at high |b|
- Better PSF, less background = improved sensitivity
- 160(P7) vs 250(P8) sources

Bottom line: ~130 sources not in 1FHL and ~250 not in TeVCat, 60 not in 3FGL
Fermi-LAT (1FGL, 2FGL, 3FGL) catalogs do an excellent job in characterizing variability and energetics of sources detected in the 0.1-100 GeV band*

*3FGL goes up to 300 GeV
Pass 8 opens a new window on the >50 GeV sky:
1. Improve PSF and Acceptance (factor of 0.5-2 in P8)
2. Low background and good (constant) PSF (0.1 deg at 68%)
3. All-sky exposure

Why a catalog of sources detected at >50 GeV?
- Allows study of the EBL, EGB, Galactic plane etc.
- Continues our effort to characterize sources at high energies
- Connects well to IACTs, HAWC and the upcoming CTA
Example of a Dark Accelerator: 2

Renaud et al. 2008

H.E.S.S. (preliminary)

2FHL J1505.1-5808

$\nu F_\nu$ [erg cm$^{-2}$ s$^{-1}$]

Energetic gamma-ray observations of AX J150436-5824 and PSR J1502-5826 using the H.E.S.S. and Fermi-LAT telescopes.
Fluctuations of the background depend also on the properties of the unresolved source population.

\[ \alpha = \text{power law index below the break} \]
Photon Fluctuation Analysis

- Fluctuations of the background depend also on the properties of the unresolved source population

- The 2FHL LogN-LogS resolves 96(+15/-18)% of the IGRB

Nearly all the IGRB is produced by BL Lacs