Gamma-ray Survey of our Universe

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NASA/MSFC
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Multi-Wavelength View of our Galaxy

[Image: Multi-wavelength view of the Milky Way showing various wavelength bands, including radio continuum, atomic hydrogen, molecular hydrogen, infrared, mid-infrared, near infrared, optical, X-ray, and gamma-ray.]
Gamma-ray View of our Galaxy

HAWC $>100$GeV

PRELIMINARY

Credits: NASA/DOE/Fermi LAT Collaboration
High Energy View of our Galaxy

- **Fermi LAT 0.05 — 2 TeV, >6 years**
- **HESS >1TeV, 10 years**
- **HAWC 0.1 — 100 TeV, 1 year**

**Credits:** NASA/DOE/Fermi LAT Collaboration

**Supernova Remnants**

**Pulsar Wind Nebulae**

**TeV Binaries**

**Supernova Remnants**

**Pulsar Wind Nebulae**

**TeV Binaries**

**Credits:** NASA / CXC / SAO / F.D. Seward, W.H. Tucker, R.A. Fesen

**Mirabel, Science, 312, 1759**
Gamma-Ray Detectors

**Wide Field of View, Continuous Operations**

- **Fermi**
- **AGILE**
- **EGRET**
- **HAWC**
- **ARGO**
- **Milagro**
- **Tibet ASγ**
- **HESS**
- **FACT**
- **MAGIC**
- **VERITAS**

**Sensitivity**

- $<0.1°$ angular resolution
- $10$ s GeV to $10$ s TeV
- $100$ GeV to $>100$ TeV
- $100$ MeV to $>100$ GeV

**Timeline**

- **Milagro** 2000-2008
- **ARGO** 2007-2014
- **Milagro** 2000-2008
- **HAWC** 2013 - present
- **Tibet ASγ** 1990-present
- **MAGIC**
- **VERITAS**
- **HESS**
- **FACT**
HAWC collaboration

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Mapping the Northern Sky in High-Energy Gamma Rays

HAWC Observatory

HAWC operates day and night, providing a large field of view for the observation of the highest energy gamma rays.

HAWC is located at 4,100 m above sea level, covering an area of 20,000 m².

Water Cherenkov tank

HAWC comprises an array of 300 tanks that record the particles created in gamma-ray and cosmic-ray showers.

Particles inside the shower produce Cherenkov radiation that is detected by the PMTs.

Gamma rays vs cosmic rays

HAWC selects gamma rays from among a much more abundant background of cosmic rays.

“hot” spots concentrate around the core
“hot” spots are more dispersed
Gamma/Hadron Separation

hadronic event
gamma ray-like event
HAWC Sensitivity

- $0.2^\circ$ PSF$_{68%}$ at highest energy
C. Michelle Hui

Gamma-ray Survey of Our Universe

Gamma-Ray Observatory

- Sensitive from 100 GeV to 100 TeV.
- Angular resolution (68% containment) 0.2-1.0 degrees.
- 2sr instantaneous field of view, 2/3 of sky each day.
- >95% duty cycle.
- **Strengths:**
  - Extreme high-energy reach.
  - Wide field-of-view: ideal for transients and extended objects.
  - High duty cycle.

High Altitude Water Cherenkov (HAWC)

- HAWC-30: began Aug 2012
- HAWC-111: Jun 2013 (~280 days)
- HAWC: Nov 2014 (341+ days)
- Inauguration Mar 2015
Milagro 8-Year TeV Sky Survey

HAWC predecessor

Crab at 17σ in 8 years.
HAWC TeV Sky Survey

- HAWC is ~15x more sensitivity with lower energy threshold compared to Milagro, and more sensitive towards Galactic center.
- Skymap from 341 days of data taken with the finished HAWC array.
- Point source analysis assuming power-law index of 2.7.
Crab Nebula at highest energies

• photons up to 80TeV reported by IACTs
• insight into magnetic field environment and efficiency of particle acceleration

60TeV photon from the Crab Nebula seen by HAWC.
Pulsar Wind Nebulae

**Geminga**

- Closest known middle aged pulsar
- Possible nearby cosmic ray acceleration site — explanation for positron excess (Yuksel et al. 2009)
- Not seen by IACTs, extent maybe larger than IACT FOV.
- Ongoing morphological and spectral studies

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*Milagro - Point Search*

*XMM, Pavlov et al. 2010*
Pulsar Wind Nebulae

**PSR J0659+14**

- New PWN seen near Geminga!
- Similar large extension seen in data.
- This pulsar is very similar to Geminga pulsar:

<table>
<thead>
<tr>
<th></th>
<th>Geminga</th>
<th>PSR J0659+14</th>
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<tbody>
<tr>
<td>age [yr]</td>
<td>3E+05</td>
<td>1E+05</td>
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<tr>
<td>distance [pc]</td>
<td>250</td>
<td>288</td>
</tr>
<tr>
<td>spin-down power [erg/s]</td>
<td>3E+34</td>
<td>4E+34</td>
</tr>
</tbody>
</table>

- Geometry and diffusion studies on propagation of electron/positron to Earth.
New TeV Sources!

New TeV emission region
2HWC J1927+187*
• ~7σ pre-trials
• current blind search algorithm identify this region associated with 2HWC J1930+188, ongoing analysis on spatial morphology

2HWC J1930+188
• coincident with VER J1930+188 (SNR G54.1+00.3 / PSR J1930+1852)
• TeV emission was reported to be point-like and likely from PWN
• nearby molecular CO cloud

New TeV source
2HWC J1928+178
• ~8σ pre-trials
• coincident with PSR J1928+1746
• tail towards unidentified source 3FGL J1925.4+1727
• VERITAS point source upper limit ~1.4% of Crab
New TeV Sources!

New TeV source
2HWC J1953+294
• confirmed by VERITAS
• potential association:
  • PWN DA 495 seen in X-rays
  • 3FGL J1951.6+2926
2HWC J2019+368 is coincident with MGRO J2019+37 and VER J2019+368
- extended emission including PSR J2021+3651 and HII region Sh 2-104

New TeV source 2HWCJ2006+340:
- >6σ pre-trials
- 0.6° from unidentified source 3FGL J2004.4+3338
two distinct TeV sources:

- 2HWC J2031+415 — TeV J2032+4130, a PWN
- 2HWC J2020+403 — VER J2019+407, UID encompassing SNR G78.2+2.1 and PSR J2021+4026
- extended emission region 2HWC J2025+410* and 2HWC J2027+403* at Fermi cocoon / ARGO superbubble region

Cygnus Region
Galactic Diffuse Emission

Diffuse contributions:
- Cosmic-ray interactions
- Molecular clouds
- Interstellar gas
- Inverse Compton
- Unresolved sources.

Leiden/Argentine/Bonn (LAB) Survey of Galactic HI

courtesy of LAMBDA


Milagro

Abramowski et al. 2014

Gamma-Ray Survey of Our Universe
A uniform surface brightness fit in addition to source model is preferred at $5.7\sigma$. The fitted surface brightness at 5 TeV is $1.6\pm0.4\times10^{-11}$ TeV$^{-1}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$. HESS average diffuse extrapolated to 5 TeV is $1.0\pm0.2\times10^{-11}$ TeV$^{-1}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$. Current limit from HAWC-111 dataset includes unresolved sources.
Large-scale structures e.g. Fermi Bubbles

- Large scale, non-uniform structures extending above and below the Galactic center.
- Edges line up with X-ray features.
- Correlate with microwave excess (WMAP haze)
- Both hadronic and leptonic model fit Fermi LAT data. Leptonic model can explain both gamma ray and microwave excess.
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- First limits in TeV, hard spectrum is highly unlikely.

extrapolated models from Ackermann 2014

Transient Search

**Crab Nebula**
- Crab flares, continue up to TeV?
- No activity in radio, IR, and X-rays.

HAWC observation:
- Data is consistent with a constant flux.
- Coincident observation with Fermi-LAT reported Crab flare starting Jan 7 2016.
- 95% C.L. upper limit on 13-day average flux above 1 TeV is 1.01x average Crab flux.

Credit: NASA/DOE/Fermi LAT/R. Buehler
Transient Search

AGN flares Mrk 421 / Mrk 501
Multi-wavelength / Multi-messenger

Have follow-up agreement with:
• Swift
• Fermi-LAT
• IACTs
• FACT
• HESS
• MAGIC
• VERITAS
• AMON
• IceCube
• ANTARES
• LIGO/VIRGO

HAWC-triggered:
• New source candidates lists.
  • follow-up observations by IACTs such as VERITAS and MAGIC from Pass 1 release.
  • Flares from known gamma-ray sources.

Externally triggered:
• IceCube alert on high confidence neutrino event (highest energy pointed astrophysical track-like).
  • Fermi alerts on flaring activities.
  • LIGO/VIRGO gravitational wave event follow-up

HAWC ATel #8922 on Mrk 501 flare

IceCube ATel: #7856
HAWC Follow-up ATel: #7868
12 NaI detectors
(8keV—1MeV)

2 BGO detectors
(200keV—40MeV)

Gamma-ray Burst Monitor

GBM:
• FOV >8sr
• Whole sky every ~90min
1404 GBM GRBs

- 1175 Long
- 229 Short
- 191 also triggered Swift-BAT

- Brightness of weak short GRBs does not appear to be redshift dependent
  - i.e. weak ≠ far away
Gamma-ray Bursts

- Collapse of a massive star or merger of two compact objects.
- Collimated relativistic outflow.
- Prompt keV-MeV emission, afterglow in other wavelengths.
- Detected ~ once per day, distributed all over the sky.
Follow-up to Gravitational Wave Event GW150914


- Untriggered sub-threshold signal 0.4s after LIGO trigger.
- Consistent with a low-fluence short GRB coming from behind Fermi.
- Poorly localized but consistent with LIGO localization.
- 0.2% post-trials probability in statistical fluctuation.
Untriggered GBM GRB search

- In addition to the directed search with LIGO events, untriggered search in the Continuous Time Tagged Events (CTTE) data is ongoing.
  - 2 µs time resolution with 128 energy channels
  - 10+ timescales: 64ms to 2.8+ s
  - multiple energy ranges
- Working towards creating automated GCNs, will be distinct from triggered events type.

[http://gammaray.nsstc.nasa.gov/mbm/science/sgrb_search.html](http://gammaray.nsstc.nasa.gov/mbm/science/sgrb_search.html)
INTEGRAL Anti-Coincidence Shield (ACS) lightcurve

- 2014-07-09 08:49:56.600
- Found in 1.40s time binning
- 25 - 494 keV energy range
- $P=7.75\times10^{-14}$

ACS native time bin

GBM timescale
GBM Candidate Event

- 2014-06-06 10:58:13.625
- Swift GRB 140606A
- Found in 0.25s time binning
- 93 - 494 keV energy range
- $P=1.91 \times 10^{-16}$

INTEGRAL ACS lightcurve

ACS native time bin

GBM timescale

Not all GBM triggered short GRB are detected by ACS.
Outlook

- Both Fermi and HAWC surveying and monitoring the gamma-ray sky in different energies, with ground-based telescopes such as VERITAS ready for follow-up.
- Many instruments from different waveband/messenger (X-rays, neutrinos, gravitational waves) available for simultaneous observation.

- HAWC observatory catalog of first year full operation is in prep (2HWC), with new TeV sources!
- Diverse science results, stay tuned!
- Upgrade to expand the array to enhance effective area >10 TeV by 3-4x is currently under installation.