The Gamma-ray Universe

Jim Hinton - MPIK Heidelberg

28th Texas Symposium on Relativistic Astrophysics, Geneva 17th Dec. 2015
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Selig+ (2015)

\[ \Gamma_\gamma \approx 2.5 \]

\[ \Gamma_\gamma \approx 2.4 \]

\[ \Gamma_\gamma \approx 2.6 \]
Gamma Ray Source Classes

Supermassive Black Holes

Radio Galaxies
Central Engine
Sgr A*
Unidentified
Gamma ray bursts
Long
Short

Star Forming Systems

Normal Galaxies
Starburst Galaxies
Satellite Galaxies
Globular Clusters

Starforming regions

Individual Objects
Binary systems

Magnetospheric Emission
Pulsars
PWN
Supernova Remnants
Black hole binaries
Novae
Pulsar binaries
Colliding winds

Solar System

Solar Flares
Moon
Terrestrial

FSRQs
BL Lacs
Other/Unknown
Radio Lobes
175 Sources
Ground-based ‘TeV’ instruments

Gamma Ray Source Classes

Supermassive Black Holes

Star Forming Systems

Molecular Clouds

Starforming regions

Normal Galaxies

Starburst Galaxies

Satellite Galaxies

Globular Clusters

Individual Objects

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Binary systems

Colliding winds

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Black hole binaries

Gamma ray bursts

Short

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Solar System

Solar Flares

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FSRQs

Blazars

Radio Galaxies

Radio Lobes

Central Engine

Sgr A*

Unidentified

BL Lacs

Other/Unknown
hadronic model

Fermi-LAT

H.E.S.S.

RX J1713.7-3946
H.E.S.S. Coll. 2015
preliminary

Fermi+MAGIC
SSC Models
Dermer 2014

MAGIC
Ansoldi et al. (2015)

Mrk 421
Fermi+MAGIC
SSC Models
Dermer 2014
Second Fermi Hard Source Catalogue

2FHL

360 sources
78 detected also by IACTs
57 new sources

60000 photons
80 months
$>50$ GeV

Fermi LAT Coll. 2015
HESS Galactic Plane Survey

- Completed 2014
  + 3000 hours of observations
  + Cf 230 hours in initial pub’s 2005/6

- Modelling with Gaussian components
  + 100 components, +13 ‘special’
  + 77 independent sources
Diffuse emission suppressed by background modelling technique

Sensitivity 0.5-2% of Crab Nebula Flux
HAWC

- Very wide field of view, very high duty cycle
  - More modest resolution and background rejection power

- Very early days but
  - Will reach comparable sensitivity to HESS survey (at ~TeV energies) for extended objects (~0.3 degrees) very quickly → huge improvement for very extended emission
  - Planned outrigger extension (2016) - improved high energy performance

→ Huge potential, exciting times
The Galactic Sources

- **Supernova Remnants**
  - Middle aged SNRs interacting with molecular clouds – proton+ acceleration
  - Young SNRs with non-thermal X-ray emission + GeV-TeV
  - Energy breaks in particle spectra for all well measured objects
  - Complete absence of >100 TeV protons (how to reach the knee?)

- **Pulsars**
  - Magnetospheric emission dominates at GeV
  - Pulsar wind nebulae
    - Dominate TeV population
    - Energy dependent morphology (electron cooling/transport)

- **Binaries**
  - Accreting systems at GeV – Novae and Cyg X-3
  - PWN in binary systems GeV+TeV
  - Colliding stellar winds – Eta Carina is an efficient hadron accelerator!

- **Star-forming regions**
  - Collective processes? Cygnus cocoon, Westerlund 1, 30 Dor
The Fermi Bubbles

- ~8 kpc GeV lobes with radio/microwave counterparts
  - Rather sharp edges
  - Uniform spectrum

- Origin?
  - Need ~$10^{55}$ erg
  - Sgr A* jet activity?
    - $L_{\text{edd}}$ for O(1000 years)
  - CMZ blown bubble?
    - Need ~$10^9$ year inflation

- Contents?
  - Electrons
    - Universality of spectrum?
    - Cooling implies distributed reacceleration?
  - Protons
    - Energy requirements?

The “GeV Excess”

- Feature in the Fermi emission from the GC region spotted by many authors
- Spectrum of excess emission resembles that of annihilating DM: implied mass ~40 GeV
- Spatial distribution ~NFW
- Implied cross-section is consistent with a thermal relic!
- BUT…
Excess above what?

- Standard diffuse model – which has many limitations/simplifications
  - Purely diffusive transport
  - Lack of CR sources in inner kpc
  - Radiation fields poorly known / modelled
  - Unresolved source populations not included (e.g. ms pulsars)
- Nevertheless
  - Excess is very DM-like in terms of spatial extent, spectrum and implied cross section – by far the best DM annihilation ‘hint’ so far
- Still a lot of work to do on foreground astrophysics
  - Deeper understanding of diffuse emission and source populations
WIMP Search Status/Prospects

Fermi-LAT Collaboration 2015

Preliminary
The TeV Galactic Centre?

- **TeV Status ~2010**
  - Point-like emission from Sgr A* (<20 arcsec)
  - CMZ diffuse emission


28th Texas Symposium on Relativistic Astrophysics, Geneva 17th Dec. 2015
The TeV Galactic Centre?

- **TeV Status ~2010**
  - Point-like emission from Sgr A* (≤20 arcsec)
  - CMZ Diffuse emission

- **New results**
  - Deep HESS obs.
    - 55 → 220 hours of data
    - + improved analysis
  - MAGIC and VERITAS
    - Confirmation+radio arc source

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[Image of TeV Galactic Centre data with annotations]

Without subtraction

1 degree

H.E.S.S. Coll. 2015

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Unidentified Source HESS J1745-303
The TeV Galactic Centre?

- Ratio of TeV flux to available target material gives CR density

Aharonian* et al. Nature 2006

Wind/Ballistic Diffusion

H.E.S.S. Coll. 2015

H.E.S.S. Coll. 2015

Diffusion

Wind/Ballistic

Projected distance (pc)

6.0 x local CR density

$1/r$

$1/r^2$

$w_{\text{Gal}(\geq 10 \text{ TeV})} (10^{-3} \text{ eV cm}^{-2})$
The TeV Galactic Centre?

- Spectrum implies proton acceleration to \( \sim \)PeV energies
- Morphology implies \( \sim \)continuous injection in central \( \sim 10 \) pc
- Energetically plausible for Sgr A* as source
- More active in the past? Would imply significant role for A* in Galactic PeV flux
  - Provided transport can work

Aharonian* et al. Nature 2006

H.E.S.S. Coll. 2015
Other supermassive black holes?

- Active galaxies dominate the Fermi-LAT source population
  - Fermi+ VLBI radio excellent combination for long term monitoring
- Most striking in TeV – very rapid (few minute) variability
  - e.g. nearby active galaxy IC 310 – with long (~300 kpc) one-sided jet
  - Recent detection of dramatic variability with MAGIC: <light crossing time of BH
    - Despite apparently reasonably large angle between jet and line of sight (~15°)
    - Implied origin of emission very close to BH

![Graph showing variability of 5 Crab](image)

MAGIC Coll. Nature 2014
Gravitationally Lensed Blazars


S3 0218+35

Credit: NASA, MAGIC
Gravitationally Lensed Blazars

- MAGIC observations triggered by Fermi flare
  - But could not observe – full moon
  - Observations scheduled for 11 days later → detection
  - Most distant >100 GeV source

- Change in flux ratio of two components likely due to microlensing
  - Can be used to place limit on size of emission region ~$10^{15}$ cm
  - Also for PKS 1830-211

Sitarek+ (MAGIC Coll. 2015)

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The Cherenkov Telescope Array

- A huge improvement in all aspects of performance
  - A factor ~10 in sensitivity, much wider energy coverage, much better resolution, field-of-view, full sky, ...
- A user facility / proposal-driven observatory
  - With two sites and a total of >100 telescopes
  - User support, open archive, FITS data products
- A major international project
  - 31 nations, >1200 scientists
  - Including the teams from HESS, MAGIC and VERITAS

Prototyping -2016, Construction 2017-2020+, Science from ~2018
CTA Sites

Cerro Armazones
E-ELT

Cerro Paranal
Very Large Telescope

Vulcano Llullaillaco
6739 m, 190 km east

Proposed Site for the Cherenkov Telescope Array

© Marc-Andre Besel

Under Negotiation
Back-up Sites
Sensitivity

Differential sensitivity (5 bins per decade in energy)

Energy $E_R$ (TeV)

$E^2 \times$ Flux Sensitivity (erg cm$^{-2}$ s$^{-1}$)
e.g. proton accelerator $\propto E^{-1.9}$ up to 1 PeV:
$\pi^0$ decay emission, $10^{50}$ erg in CRs, $n=1\text{cm}^{-3}$, 2.5 kpc
First Cherenkov Light

- Inauguration 1st December 2015
- First Cherenkov movies 26th November 2015
First Cherenkov Light
\( \gamma + \gamma \rightarrow e^+e^- \)

Mean free path due to gamma-photon pair creation

\[ \text{Energy} \times 10 \text{ x Sensitivity, Large Collection Area} \rightarrow \text{all topics} \]

\[ \text{Energies down to 20 GeV} \rightarrow \text{Cosmology++} \]

\[ \text{Rapid Slewing in 20 seconds} \rightarrow \text{transients} \]

\[ \text{Energies up to 300 TeV} \rightarrow \text{Pevatrons} \]

\[ \text{8° Field of View} \rightarrow \text{surveys, extended objects} \]

\[ \text{10% Energy Resolution} \rightarrow \text{lines, features} \]

\[ \text{Few }^\circ \text{ Angular Resolution} \rightarrow \text{morphology} \]

NASA

Supersymmetric neutralinos

\[ \begin{align*}
\text{Leptons} & \\
\text{Neutrinos} & \\
\text{Anti-protons} & \\
\text{Protons} & \\
\end{align*} \]

Decay process

A2/A1 = 100 gamma = 2.0 cutoff = 300 TeV
Multi-component detector for gamma-ray astronomy and cosmic ray studies to be constructed in Sichuan province of China (4.3km asl)
- 1% prototype at ARGO site in Tibet is running
- Deployment starting in 2016, completion ~2021
...and MeV?

- Worst covered part of the EM spectrum, with a lot going on
  - AGN, GRB, SNR, +++
- Many mission concepts
  - MEGA, GRIPS, SMILE, DUAL, ASTROGAM
- e.g. COMPAIR
  - 0.5-500 MeV explorer
  - Compton scattering and pair production telescope
  - Extensive use of technology from Fermi / AGILE
    - Silicon strip tracker ++
- Real chance to get a new MeV mission late 2020s
Conclusions

- Gamma-ray astronomy is a vibrant observational field
  - Huge recent observational progress and a long list of major puzzles
  - ‘Old instruments’ – Fermi + IACTs still delivering

- Huge promise for the next decade
  - CTA on track - and will have a transformational impact, and be the first real open observatory in the TeV waveband
  - As part of a golden age for non-thermal astrophysics / astroparticle physics: SKA, eROSITA, Athena, IceCube, Km3Net, ALIGO +++