Ground-Based Gamma-Ray Astrophysics

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Goals of VHE Astrophysics

- Cosmic Particle Acceleration
  - Origin of cosmic rays
  - Understand astrophysical jets and extreme environments
  - VHE Pulsar emission

- Cosmology
  - Measure the extragalactic background light

- Search for new physics
  - Dark matter (indirect detection of annihilation or decay products)
  - Measure intergalactic magnetic fields (origins in primordial field)
  - Search for violations of Lorentz invariance
  - Astrophysical backgrounds
Gamma Ray Telescopes

**Atmospheric Cherenkov Telescopes**
H.E.S.S./VERITAS/MAGIC

- 50 GeV - 100 TeV
- Large Area
- Excellent background rejection
- Small Aperture/Low Duty Cycle
- Study known sources
- Deep surveys of limited regions
- Source morphology (SNRs)
- Fast transients (AGN flares)

**EAS Arrays**
Milagro/Tibet/ARGO

- 100 GeV - 100 TeV
- Large Area
- Good background rejection
- Large Aperture & Duty Cycle
- Sky survey & monitoring
- Extended Sources
- Transients (GRBs, AGN flares)
- Highest Energies (>10 TeV)
Extensive Air Showers

- $\gamma$ showers almost purely e-m and relatively compact
- Hadronic showers contain muons ($\sim 30/\text{TeV}$)
- Both have core of energetic particles
- Ground-based VHE telescopes must distinguish protons from photons

F. Schmidt, "CORSIKA Shower Images", http://www.ast.leeds.ac.uk/~fs/showerimages.html
Imaging Atmospheric Cherenkov Telescopes

- Cherenkov light beamed forward (~1° opening angle)
- Illuminates ~100,000 m² on ground
- Cherenkov flash lasts ~few ns
- $O(10 \text{ photons/m}^2)$ @ 1 TeV
Extensive Air Shower Arrays

- Detect particle that survive to ground level
- Scintillation detector arrays sparsely instrument the ground <2% coverage
- Water detectors (or RPC carpet) can densely sample the shower particles (~50% particles detected)
- Water will also convert gamma rays to electrons/positrons (gamma rays dominate the particles on ground ~6:1)
- Deep water detector (≳4m) can serve as muon detector
Angular and Energy Reconstruction

Primary energy via energy at ground (shower fluctuations dominate resolution ~40%)

Direction via timing (~ns timing yields 0.2°-1° resolution)
VHE Instruments

- Milagro
- MAGIC
- Tibet ASy & ARGO
- VERITAS
- HAWC
- HESS
VHE Sky

http://tevcat.uchicago.edu

178 sources
Galactic Gamma-Ray Sources

- 36 PWN (2 pulsars)
- 35 UNID
- 13 SN Shell
- 10 SNR/Mol. Cloud
- 6 binaries
- 4 massive star clusters
- 2 Star Forming Regions
- 1 Globular Cluster

- PWN: Crab Nebula
- SNR: Tycho
- Globular Clusters: Terzan 5
- SNR/Molecular Clouds: IC 443
- X-Ray Binary
Cosmic-Ray Origins

- Steep spectrum $E^{-2.7}$
- Galactic energy loss of $10^{41}$ ergs/sec (from lifetime measurements)
- Supernovae long suspected GCR source
  - Energy budget $10^{51}$ ergs/30 years = $10^{42}$ ergs/sec
  - Strong shocks yield $E^{-2.1}$ spectrum
  - Maximum energy $\sim 10^{16}$ eV
- Direct proof has been elusive!

Fluxes of Cosmic Rays

(1 particle per m²-second)
Knee
(1 particle per m²-year)
Ankle
(1 particle per km²-year)
X-Ray Image of RX J1713.7-3946

ASCA
Deep exposures of Cas A: Radiation Models

Kumar, ICRC 2015

Hadronic model is preferred at lower energy (Yuan et al. 2013)

At higher energy both leptonic and hadronic mechanisms may contribute (Saha et al. 2013)

VERITAS-ICRC 2015

Energy (eV)

Kumar, ICRC 2015
SN Remnant Evolution

from S. Funk

- >3000 yrs
- 1000-3000 yrs
- <1000 yrs

G. Sinnis

European Cosmic-Ray Symposium, September 2016
SNR and Cosmic Rays

• SNRs are complicated objects:
  - Age, environment, progenitor, magnetic fields all may play a role
• Likely leptonic and hadronic acceleration
• Need multi-wavelength observations to understand:
  - particle energy distributions
  - X-ray - TeV correlation
  - broadband energy spectrum
• No evidence for PeV energies
• Higher spatial and energy resolution needed - CTA
Pulsars and Their Nebulae

- PWN are most common Galactic source of TeV gamma rays
- PWN are powered by their pulsars
- Nebulae trap high-energy electrons/positrons
- Eventually release electrons/positrons into the ISM
- Potential background for dark matter searches
- Understanding particle diffusion critical
VHE Emission from Pulsars

from Dany Page

G. Sinnis

European Cosmic-Ray Symposium, September 2016

Carolee Anne Bostock
Crab Pulsar >400 GeV Emission

Pulsed emission in the 120-400 GeV range not expected theoretically – challenge to pulsar models.

VERITAS, Nguyen, ICRC 2015
MAGIC, de Oña Wilhelmi, ICRC 2015

MAGIC
VERITAS
Crab Pulsar VHE Spectrum

VHE emission challenges Pulsar models
Vela Pulsar: H.E.S.S. II

- H.E.S.S. measurement at 10 GeV!
- Spectrum consistent with Fermi
- No evidence of hard component
Pulsar Wind Nebulae

- Rapidly spinning neutron star powers a cold relativistic electron-positron wind
- Wind termination shock accelerates $e^+e^-$
- Inverse Compton reactions lead to production of VHE gamma rays
- Over time nebula expands, magnetic field weakens, and $e^+e^-$ are released into the ISM

Gaensler & Slane 2006
PWN: Positron Generators

- Geminga (~300,000 yrs at ~200 pc) and Monogem (100,000 yrs at ~300 pc) are good candidates
- Milagro detected (HAWC confirmed) an extended gamma ray source (3°) coincident with the Geminga pulsar (~10^50 ergs/sec) at ~20 TeV. Most likely seeing the PWN.
- Understanding diffusion important for understanding role of PWN in local positron flux
Extragalactic Gamma Rays

- Active Galaxies (67 detected in VHE band)
  - Extragalactic Background Light
  - Primordial Magnetic Fields
  - Axion-like Particle Searches
  - Lorentz Invariance Violation
- Gamma Ray Bursts (not yet detected from ground)
  - Lorentz Invariance Violation
AGN Spectral Energy Distribution

Markarian 421
A. A. Abdo et al. 2011 ApJ 736 131

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Extragalactic Background Light

Gamma-rays from jet of Quasar

Observed spectrum

high absorption

low absorption

Emitted spectrum

Energy Flux

Energy

Background light

from CTA and MPI
The EBL

- The sum of all UV, optical, and IR radiation emitted over the history of the universe
- Main contributions from stars and light re-radiated by dust
- Direct measurement difficult due to local backgrounds (zodiacal light)
- Gamma-ray absorption measurements are the best way to measure EBL
- EBL is useful tool for probing other physics
  - Axion-like particles
  - UHECR accelerators
  - IGMFs
Redshift of TeV AGN

Redshift Distribution of VHE AGN

MAGIC Telescope
Redshift and Spectrum

In Fig. 10 we show the (de-absorbed) energy density spectra of Mkn 421 multiplied by an EBL model spread. The evolution of the MWL SED is studied in the frame of an external Compton emission model. The absorbing medium can be translated into EBL density constraints as shown in Fig. 7. For comparison with previous observations of Mrk 421 (2000-2001), high energy substantially change in the instrumental energy scale, the measured spectrum is corrected for the instrument's absolute energy scale.

Under the assumption that no curvature is present in the absolute energy scale of the instrument is considered, while the estimated scaling on the optical depth can be translated into EBL density constraints as shown in the right panel of the figure. The de-absorbed spectrum (shown by filled black circles) and the stacked spectrum are clearly curved, its probability of being a single power law is 1.6 times. Only periodical cutoffs are considered, while the opacity (Domínguez et al. 2011, D11) was considered (without upper limits). The best fit is marked with solid vertical lines and the dashed lines show the best-fitting PWL, respectively. The gray shaded area accounts for the uncertainties derived by the use of different spectral shapes.
EBL Measurements

- H.E.S.S. has measured the EBL from 2-1-10 microns
- Fermi has measured the EBL below 0.2 micron \(3\pm1\ \text{nW m}^{-2} \text{ sr}^{-1}\) at \(z=1\)
- These values are close to the lower bounds set by Galaxy counts
- Large star formation rates at the end of the cosmic dark ages excluded
Future Challenges

- Pulsar emission - is Crab only VHE pulsar? How is VHE emission generated?
- PWN - can they explain the local positron flux?
- What role do environment, age, and progenitor play in the acceleration of cosmic rays/electrons in SNR?
- Where are the cosmic Bevatrons?
- How do AGN jets generate multi-TeV gamma rays?
- Do gamma-ray bursts emit TeV gamma rays?
- What are the sources of the IceCube neutrinos?
- Do gravitational wave sources emit VHE gamma rays?
- How well can we constrain the EBL? (Exclude ALPs)
- Was there a primordial magnetic field?
- What is the nature of the dark matter?
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