Experimental Techniques

- Balloon
- Satellite (Fermi/GLAST)
- Cherenkov Telescopes (VERITAS)
- Air shower array (Milagro)
Čerenkov radiation is electromagnetic radiation emitted when a charged particle (such as an electron) passes through an insulator at a speed greater than the speed of light in that medium.
Shock Wave

Credit: Science 2.0
The Atmospheric Cherenkov Technique

Clue: imaging the cascade geometry → photon direction intensity → photon energy shape → cosmic ray rejection
Physics of Extensive Air Showers

Gamma-ray shower

Cosmic Ray (example proton)

Atmospheric Nucleus

(≈50 secondaries after first collision)

Electromagnetic Shower
(mainly γ-rays)

γ

π^0

π^-

π^+

Hadronic Shower
(on earth mainly muons and neutrinos)

μ^+ (~4 GeV, ~150/s/cm²)
ν_μ

Reshmi Mukherjee
VERITAS Cherenkov Telescope

- **Sensitivity:** 1% Crab in ~25 hr
- **Energy range:** 100 GeV to 30 TeV

106 m² tessellated
Re-coated every ~4 years

499 PMTs

500 MSps sampling
FADCs 3-level trigger

Reshmi Mukherjee
Quantum Physics in Action

Photomultiplier tubes (PMTs) from Hamamatsu Photonics

Photoelectric Effect: Light Matter Interaction
A VERITAS Shift

Graduate student Gunest Senturk in the VERITAS control room

Reshmi Mukherjee
The Universe through $\gamma$ rays

- Gamma-ray sky surveys and catalogues
- Pevatrons & Tevatrons in the outer Galaxy
- Relativistic Jets
Fermi-LAT $\gamma$-ray sky

Gamma ray sky above 600 MeV in Galactic coordinates

- Log flux (red ~ 1 GeV. Blue ~ 300 GeV).
- Galactic diffuse emission dominates (~80% in the GeV range), below TeV energies.
- $\gamma$-rays from CRs interacting with the Galactic interstellar gas, via neutral pion decay.
- Diffuse emission also seen at TeV energies by H.E.S.S. (inner Galaxy) and by HAWC (Galactic Plane).
Fermi-LAT γ-ray sky

- 3033 Sources in 3FGL Catalog
- > 5000 sources > 100 MeV
- > 1550 sources above 10 GeV (3FHL)

4th source catalog
50MeV-1TeV (8 yrs)
arXiv:1902.10045_v3

NASA/DOE/Fermi-LAT

- > 5000 sources > 100 MeV
VHE $\gamma$-ray Sky

- ~200 GeV and/or TeV emitters discovered
- representing 10+ source populations

All gamma-ray sources are particle accelerators - factories of relativistic matter.

- Cosmic plasmas are easily heated up to keV temperatures (X-ray).
- Thus, particles (electrons and protons/nuclei) can be easily accelerated to TeV energies - almost everywhere!

Reshmi Mukherjee
Gamma-Ray Surveys: H.E.S.S. GPS

The deepest and most comprehensive, high resolution ($\sim 0.1^\circ$) and sensitive (<2% Crab Nebula) survey of the Milky Way in very-high-energy $\gamma$-rays.

- The Milky Way is aglow with TeV $\gamma$-ray emission!
- 78 sources, 36 unidentified. Different classes of Galactic sources.
- Population studies are now possible.

Reshmi Mukherjee, ICRC, Madison, Wisconsin, 2019
Supernova Remnants

- Detected at sub-TeV, TeV, sub-PeV
- Several young shell-type SNRs detected, but the main question “whether SNRs are main contributors to GCRs?” is not yet resolved.

RX J1713.7–3946

IC 443
VERITAS Collaboration
Cosmic rays?

- Fermi-LAT SED cutoff around 200 MeV, "pion bump," is direct indication of hadronic interactions.

IC 443

Offers a compelling way to detect the acceleration sites of protons.

- Fermi-LAT SED cutoff around 200 MeV, "pion bump," is direct indication of hadronic interactions.
**Unique Capabilities: Short time scale variability**

- Locating the emission region in the jet.
- Measuring minute-scale variability.

**PKS 2155-304**
- Peak flux \(~15\) x Crab
- Doubling times \(~1\) - \(2\) min
- \(R_{BH}/c \sim 1...2 \times 10^{4}\)

**BL Lac: Major flare in Oct 2016**
- 150% Crab flux, \(\tau \sim 36\) min.
- 43 GHz VLBA imaging, coincident knots
- \(R < c t \delta/(1+z) < 12 \ R_{Sch}.\)

Classic flare from PKS 2155-304, still unbeatable!
**Intergalactic Magnetic Field (IGMF)**

- How to produce strong B fields in galaxies/galaxy clusters?
  → IGMF as seed field?
- Produced in early universe
- Probe earlier era than CMB
- Search for IGMF-broadened cascade emission
- EBL produces e+e- pair, secondary particles bent by IGMF

- Search for angular extension in 7 BL Lacs
- → Exclude IGMF strengths (5-10)$\times10^{-15}$ G at 95% CL

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Search for IGMF:
- Produced in early universe
- Probe earlier era than CMB
- Search for IGMF-broadened cascade emission
- EBL produces e+e- pair, secondary particles bent by IGMF

Cascade Emission:
- $\gamma_{EBL} \rightarrow e^+e^-$ deflected by IGMF
- $e_{CMB} \rightarrow \gamma$ (inverse Compton)

Three signatures:
- Spectral energy distribution
- Angular profile
- Arrival time

Cascade simulation of Weisgarber 2012

- Search for angular extension in 7 BL Lacs
- → Exclude IGMF strengths (5-10)$\times10^{-15}$ G at 95% CL

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Reshmi Mukherjee
Conclusion ...
The New Astronomy (c1609)
The New Astronomy (c2007)
From Current Arrays to Future

- Light pool radius $R \approx 100-150\text{m}$
  $\approx$ typical telescope Spacing

- Sweet spot for best triggering & reconstruction...
- most showers miss it!

- Large detection Area
- More Images per shower
- Lower trigger threshold
Cherenkov Telescope Array

light pool radius \( R \approx 100 - 150 \text{ m} \)

\( \approx \) typical telescope spacing
Aplanatic, Wide-Field Telescope

US Groups in collaboration with international partners are building an innovative telescope.
To fully realize scientific potential of MST array in CTA, a new, dramatically different, telescope optical system is needed, which would fully exploit IAC technology and enable operation at its limits.
Some exciting news!

Scientists Detect Crab Nebula Using Innovative Gamma-Ray Telescope

First-of-its-kind telescope promises to shed new light on the physics of high-energy phenomena, from supernovae to dark matter.

By Carla Cantor
June 01, 2020
Amado, AZ - Expected to see first light in early 2019, a prototype Schwarzschild-Couder Telescope (pSCT) for gamma-ray astronomy will be unveiled in a special inauguration event on January 17, 2019 at the Center for Astrophysics | Harvard & Smithsonian, Fred Lawrence
Thanks to the VERITAS Collaboration

Please check out: http://veritas.sao.arizona.edu
Stay tuned for some exciting fireworks in the future!