OUTLINE

• Introduction
  ▪ **Messengers, energy scales, & questions.**

• Detecting Very High Energy (VHE) particles

• GeV and TeV Astrophysics
  ▪ **Power sources & particle acceleration.**
  ▪ **Cosmic accelerators: pulsars, SN, active galaxies …**

• Physics beyond standard models (brief)
  ▪ **Dark matter, GUT particles, etc.**

• Latest results – HESS telescope array

• Future – VERITAS & GLAST.
Cosmic Ray Spectrum

- Total, diffuse spectrum.
- Power-law $E^{-3}$ differential.
- $E > 10^{20}$ eV.
- Energy density $\sim 1$ eV / cm$^3$.
- What about $\gamma$-rays and neutrinos?

New component?
At the Highest Energies $10^{20}$ eV

Particles $E > 10^{20}$ eV are not expected:

1. Very hard to accelerate to these energies.

2. Nuclei cannot travel beyond 100 Mpc

$p \gamma_{\text{cmb}} \rightarrow \Delta^+ \rightarrow \pi'$s

What are these particles and where do they come from? ... we don’t know!
Impact of High Energies

Phenomenological

High energy is reached by either:

1. Non-thermal, radiative processes (Astrophysics).

2. Decays, interactions from higher scale (Particle Physics).

Experimental

1. Particles are detected by total absorption.

2. We are required to measure tiny fluxes.  
   (< 1 /km²/century at highest energies).
1. Galaxies have magnetic fields.
   • Protons and nuclei will be deflected by the $\mu$G galactic B field.
   
   Larmor radius $r = \frac{R}{cB}$

<table>
<thead>
<tr>
<th>$R$</th>
<th>$r$</th>
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<tbody>
<tr>
<td>$10^{15}$ eV</td>
<td>0.3 pc</td>
</tr>
<tr>
<td>$10^{20}$ eV</td>
<td>30 kpc</td>
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   ← size of galaxy

2. Intergalactic fields may also be significant.
   • Clusters (e.g. Coma) have field strengths $B \sim 0.1 – 2 \mu$G, perhaps extending out along sheets and filaments.

We need neutral particles to do astronomy $\rightarrow \gamma, \nu$
Key Questions

1. What is the origin of the diffuse flux of cosmic-ray particles?
   - We don’t know, but the sources must be both powerful and renewable. We have no real understanding of physics mechanisms.

2. Can VHE particles provide clues about the early Universe or about the physics at higher mass scales?
   - Yes, via absorption features, new particles (e.g. dark matter) …

3. What new astrophysics is revealed in VHE $\gamma$-rays?
   - Gamma-rays point directly back to sites of extreme particle acceleration and unexpected phenomena.
   - Gamma-ray beams can be used to probe radiation fields and the fabric of space-time.
DETECTION OF VHE PARTICLES
Experimental Techniques

- Balloon
- Satellite
- Cherenkov Telescopes
- Air shower array
- Ice/Water Cherenkov
Compton Gamma-Ray Observatory

- Very successful mission.
- EGRET detected ~ 300 points sources.
Air Showers

γ-ray

0.01 to 100 TeV

The Atmosphere
Cherenkov Telescopes

$\gamma$-ray

0.01 to 100 TeV

The Atmosphere

$\theta \sim 1.5^\circ$

Area = $10^4 - 10^5$ m$^2$

$\sim 60$ optical photons/m$^2$/TeV
Whipple $\gamma$-ray Telescope

Whipple 10m (Arizona)

$E_{th} \sim 300$ GeV

PMT camera

Cherenkov Image – Background rejection.
Cosmic Ray Rejection $\sim 300$
Solar Mirror Arrays I

- Large Mirror Area
- Low E Threshold
- ~ 100 GeV

STACEE (New Mexico)

Cosmic Ray Rejection ~ 100

1 GHz Flash ADCs
Solar Mirror Arrays II

Keck Solar Two
(Barstow, CA)

Heliostat Field: > 2,000 mirrors
GeV and TeV Astrophysics
GeV $\gamma$-ray Sky

- ~ 300 HE point sources, most unidentified.
- Most identified sources are AGN – “Blazars”
All discovered by Cherenkov telescopes.
(CANGAROO in S. Hemisphere)
• No sources yet.
Power Sources

Broadly speaking, there are two types of sources:

1. Electromagnetic
   - e.g. rotating highly magnetized object – *Pulsar* (1)

2. Gravitational
   - Core collapse of a massive star – *SN and its remnant* (2)
     - Gamma-ray Bursts … etc.
   - Accretion onto a compact object – *Active Galactic Nuclei* (3)
     - Microquasars … etc.

Intertwined – eventually acceleration is done electromagnetically, and often both are involved.
1. Pulsars

Crab Nebula

→ Particle acceleration by pulsar and by the nebula wind.
2. Supernova Remnants (SNR’s)

- Collapse of massive star.
- Outer layers ejected with $v \sim 1\text{-}2 \times 10^4 \text{ km/s}$.
- Shell expands and shock front forms as it sweeps up material from ISM.
- Acceleration of particles via “canonical” Fermi process.
- In $\sim 10^4$ yrs, blast wave begins to deccelerate (Sedov phase) and slowly dissipate.
SNR’s – Acceleration and Propagation

VHE gamma rays from secondary interactions:
- $p$: $\pi^0$ production and decay
- $e$: Inverse Compton scattering and Bremsstrahlung

Trace beam density $\times$ target density
3. Active Galactic Nuclei (AGN)

AGN are very luminous galaxies with a bright central core.

- Likely powered by accretion onto BH’s of $10^6 – 10^9$ solar masses.
- Released accretion energy powers jets of relativistic outflow.
- Particle acceleration (e,p) occurs in these jets $\rightarrow$ beams of $\gamma$’s, $\nu$’s.
Jet in M87
Understanding AGN

How do Jets form & what powers them?

Nature of beam:
- energetics $\Gamma$
- particle type: $e$ or $p$
- field strengths $B, \gamma$

Geometry & External:
- emission zones
- source of soft photons

Earth
AGN Observations

Mrk 421 Whipple

“BLAZARS”:

- Powerful, radio-loud objects.
- Highly variable at all wavelengths.
- Jets – superluminal motion beamed emission to Earth.
- STACEE detected similar rapid variability.
- Shortest variations probe to \( \sim 10^{-4} \text{ pc} \), within a factor of ten of Schwarzschild Radius.
• VHE Flares are generally well correlated with X-ray flares.

• But not in this case!
AGN: Broadband Spectrum

Mrk 501

γ-ray and X-ray correlation is most easily explained in Synchrotron-IC scenarios.

→ Same e⁻ population.

Constraints on electron Γ, time scales, emission zones, soft photon density, etc.

Starting to get a detailed understanding of these sources.
Cosmic Absorption

Gamma-rays will pair-produce off intergalactic radiation fields.

\[ \gamma \gamma \rightarrow e^+ e^- \]

1 TeV \hspace{1cm} 1 eV (1.2 \mu m)

Hauser & Dwek 2001

Diffuse radiation fields

Model \( \gamma \)-ray spectra

(Primack et al. 1999)
New Physics Origins

So far – only talked about astrophysical sources of VHE particles. Also exist New Physics possibilities.

1. Particle Physics at higher mass scale, e.g.
   - Supersymmetry (Dark Matter).
   - Top-down sources (GUT scale particles).

2. Relics from early Universe, e.g.
   - Primordial black holes.
   - Decaying heavy neutrinos.

These are very intriguing, but speculative.

Also speculation on probing quantum gravity using distant sources of HE photons.
Dark Matter & SUSY

Neutralinos can have enhanced density in GC.
Annihilate to give $\gamma$-rays at GeV and TeV energies.
Generally expect broad “bump” in $\gamma$-ray spectra.

Flux $\sim \left( \frac{\rho_x}{M_x} \right)^2 \sigma v$
Latest Results
NEW Telescope Arrays (2004)

HESS (Namibia)
4 x 12m Telescopes

HESS:
\[ E_{\text{th}} \approx 120 \text{ GeV} \]
Ang. resolution \( \approx 4' \)
E resolution 10-15%
CR rejection > 5,000

Sensitivity:
10x better than Whipple.
TeV $\gamma$-ray Sky c2005

New Scorecard:
- 2 pulsars
- 4 SNR's
- 8 AGN
- 5 others
- 19 total

- New HESS Sources (8)
- Excluded by HESS (3)

+8 more Sources! (3/27/05)
1. SNR RX J1713 with HESS

Confirmed in 2004:
- 4 telescope data
- First extended \(\gamma\)-ray source
- Emission \(\sim 1^\circ \varnothing\)
- Flux 65% Crab
- > 40 \(\sigma\)
- Confirmed flux

Good correlation with X-ray image.

Real test of origin of CR’s.
Precise Map of RX J1713
2. Galactic Center

HESS Confirmed 2004
- ~ 50 hours 4 tel data
- > 40σ

Point source
- radius < 0.1°
- accurate position

Hard, flat spectrum
- Γ = 2.21 ±0.09 ±0.1

Dark Matter speculation…
Sgr-A* and Sgr-A East

- Position compatible with Sgr A*
FUTURE
Major HE $\gamma$-ray Telescopes

GLAST (2007)

VERITAS

MAGIC

HESS

CANGAROO
GLAST – Satellite Telescope

GLAST LAT Instrument:
- Si-strip tracker
- CsI calorimeter
- Anti-coincidence veto

Simulated sky map from 1 year survey.

Launch in 2007.
VERITAS

Collaboration: 80 scientists
U.S, Canada, U.K., Ireland

Detector Design:
• Four 12m telescopes.
• 500 pixel cameras (3.5°).
• Site in southern Az (1700m),
• Fully operational in 2006.

Some characteristics:
• Energy threshold ~ 100 GeV.
• Ang. resolution ~ 4’.
• Crab rate ~ 50 γ/min.
  (detection in 20s).
Prototype telescope (2004)

- All major systems tested.
- Several months of observations.
1st Cherenkov Images

- End-to-end test of system.
- HESS does not have this capability.
Telescope 1

Whipple Base Camp
Mt. Hopkins, AZ

Telescope 1 (operational Feb 05)
Telescope 1

Crab Detection: \( \sim 10 \sigma /\sqrt{\text{hr}} \)
Kitt Peak Site (April 2005)
Bumps in the Road

VERITAS has had three major road-blocks (so far):

1998 Project proposed
2000 Decadal Survey, SAGENAP give high rating
2001 Ritz review goes well
Smithsonian forced to reduce funding
2003 Blandford review goes well
Unable to secure site on Mt. Hopkins
Invited to Kitt Peak (NSF/NOAO) Construction starts
2004 Prototype telescope operational
2005 Telescope 1 operational

Lawsuit regarding Kitt Peak site
2006 ??
VERITAS … will have sensitivity for time-resolved spectral measurements on hourly time scales.
Telescope 1 Movies

Run: 574  Event: 897  GPS: 63 : 3 : 56 : 57.94600
Max channel 500
Num Samples 48
Num Trigger 7
Num Tubes 12
Num Dead 55

γ-ray

GEO: c_x=0.27, c_y=0.58, dist=0.63, length=0.1599, width=0.0763, α=2.98, size=811.76
Telescope 1 Movies

Run: 574 Event: 34 GPS: 63 : 3 : 56 : 45.59971
Max channel 500
Num Samples 48
Num Trigger 54
Num Tubes 44
Num Dead 55

GEO: c_x=0.07, c_y=-0.00, dist=0.07, length=0.9564, width=0.3997, a=33.97, size=2189.19

Cosmic Ray
Telescope 1 Movies

Max channel 500
Num Samples 48
Num Trigger 19
Num Tubes 47
Num Dead 55

Muon Ring

GEO: c_x=0.73, c_y=0.07, dist=0.73, length=0.6909, width=0.5157, α=75.47, size=2350.66
Summary

- VHE particles provide unique tests of the limits of physical laws. Probe astrophysics in regimes not yet explored.

- Full survey of the sky at GeV energies exists. At TeV energies, we have detected some remarkable phenomena – many sources now and beginning to answer some important questions … still, most of the sky remains unexplored
  - New Instruments: HESS, VERITAS, & GLAST.

- Great potential for discovery of physics beyond our standard models. (But, this physics is not yet required).

“The real voyage of discovery consists, not in seeking new landscapes, but in having new eyes.”

Marcel Proust (1871-1922)