The Extreme Universe
(The Limits of Particle Physics and Astronomy)

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OUTLINE

• Introduction
  ▪ Messengers, energy scales, & questions.

• Detecting Very High Energy (VHE) particles

• Physics: Origin of VHE particles
  ▪ Power sources & particle acceleration.
  ▪ Probing particle physics and cosmology

• Astrophysics: Sources and what not
  ▪ $\gamma$-ray and $\nu$ skies at TeV energies.
  ▪ Active galaxies and dark matter.

• Future
# Cosmic Messengers

We know about the Universe primarily from:

<table>
<thead>
<tr>
<th>Particles</th>
<th>charge</th>
<th>status</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Photons</td>
<td>neutral</td>
<td>crucial</td>
</tr>
<tr>
<td>2. Cosmic Rays</td>
<td>charged</td>
<td>v. important</td>
</tr>
<tr>
<td>3. Neutrinos</td>
<td>neutral</td>
<td>developing</td>
</tr>
<tr>
<td>4. Grav. Waves</td>
<td>neutral</td>
<td>infancy</td>
</tr>
<tr>
<td>5. (New stable particle)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Energy Scales

- Planck
- GUT
- EW
- Now

Time (sec)
10^{-45}
10^{-40}
10^{-35}
10^{-30}
10^{-25}
10^{-20}
10^{-15}
10^{-10}
10^{-5}
1
10^5
10^3 yr
10^9 yr

Temp. (°K)
10^{-40}
10^{-35}
10^{-30}
10^{-25}
10^{-20}
10^{-15}
10^{-10}
10^{-5}
1
10^5
10^3 yr

Energy (eV)
10^{27}
10^{24}
10^{21} (ZeV)
10^{18} (EeV)
10^{15} (PeV)
10^{12} (TeV)
10^9 (GeV)
10^6 (MeV)
10^3 (keV)
10^{-3}

Energy (eV)
10^{-3}

Phitons
Cosmic Rays

High-Energy →

Gamma rays
CR’s

X-rays
optical
CMBR

Photons

Now
**Cosmic Ray Spectrum**

- Total, diffuse spectrum individual species not resolved.
- Power-law spectrum $E^{-3}$ differential.
- $E > 10^{20}$ eV.
- Energy density $\sim 1$ eV / cm$^3$.
- What about gammas and neutrinos?
At the Highest Energies

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??
HE Implications

Phenomenological

Energy scale is reached by either:

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

2. Decays, interactions from higher mass 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).
Magnetic Fields

1. Galaxies have magnetic fields.
   - Protons and nuclei will be deflected by the $B \sim 3 \mu G$ galactic field.
   
   \[
   \text{Larmor radius } r = \frac{R}{cB}
   \]
   
   \begin{tabular}{c c}
   \text{R} & \text{r} \\
   $10^{15} \text{ eV}$ & 0.3 pc \\
   $10^{20} \text{ eV}$ & 30 kpc \ (	ext{size of galaxy})
   \end{tabular}

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.

Charged CR directions will be scrambled by $B$ fields.

**We need neutral particles to do astronomy $\Rightarrow \gamma, \nu$**
Questions

1. What is the origin of this diffuse flux of cosmic-ray particles?
   - Abundant, extremely energetic particles. Sources must be both powerful and renewable.
   - At highest energies – we have no understanding of how they can be produced.

2. Do these particles provide clues about the early Universe or about the physics at higher mass scales?

3. What can we learn from Astronomy at very high energies?
   - Gamma-rays, ν’s point directly back to sites of extreme particle acceleration or unexpected phenomena.
   - VHE particles can be used to probe radiation fields and the fabric of space-time.
DETECTION OF VHE/UHE PARTICLES
Experimental Techniques

- Balloon
- Satellite
- Air shower array
- Ice/Water Cherenkov
- Cherenkov Telescopes

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EGRET (CGRO)

CGRO

- Very successful mission.

EGRET

- Energy range 30 MeV – 20 GeV.
- Small collection area.
- Detected ~ 300 sources.
Cherenkov Telescopes

\[ \text{Area} = 10^4 - 10^5 \text{ m}^2 \]

\[ \sim 60 \text{ optical photons/m}^2/\text{TeV} \]

\[ \theta \sim 1.5^\circ \]

Whipple 10m (Arizona)

PMT camera

ns electronics

Cherenkov image
Isolating $\gamma$-rays

Shower profile in atmosphere

Proton shower movie

$\gamma$-ray shower movie

Mrk 421 2001

Rejection Factor $\sim$ 300 (single tel)

Orientation angle ($\alpha$)

$\gamma$-rays

cosmic rays

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Brown Colloquium 1 Mar 2004
ORIGIN OF THE PARTICLES
To build a HE cosmic accelerator, we need the following parts:

1. Injection
2. Power Source
3. Acceleration
4. Propagation

Emission
Power Sources

Broadly speaking, there are two types of sources:

1. Electromagnetic
   - Rotating highly magnetized object (Pulsar)

2. Gravitational
   - Core collapse of a massive star – SN and its remnant
     - Gamma-ray Bursts
   - Accretion onto a compact object (BH, NS, etc.)
   - other…

Somewhat intertwined – eventually acceleration is done electromagnetically, and often both are involved.
Power Source: Pulsar

Crab Nebula
Supernova Remnant

- Collapse of massive star.
- Outer layers ejected with $v \sim 1-2 \times 10^4$ km/s.
- Shell expands and shock front forms as it sweeps up material from ISM.
- In $\sim 10^4$ yrs, blast wave begins to decelerate (Sedov phase) and slowly dissipate.

SNR E102
Active Galactic Nuclei (AGN)

- AGN are likely powered by accretion onto BH’s of $10^6$ – $10^9$ solar masses.
- Matter falling in piles up in rotating accretion disk. Released energy powers jets of relativistic outflow.
- Leading candidate as a source of UHE cosmic rays and neutrinos.
Fermi Acceleration

A variety of mechanisms have been proposed to explain how HE particles are accelerated in astrophysical environments.

Leading contender: Fermi acceleration.

- Shock moves rapidly through ISM.
- HE particles move back and forth across shock, gaining energy.
  First-order Fermi acceleration $\sim (V/c)$.
- Naturally get power-law spectrum.

Applied to SN remnants, acceleration time $\sim 10^4$ yrs, we reach a limiting energy:

$$E_{\text{max}} < Z \times 10^{14} \text{ eV}$$

Very hard to go higher!
Beyond the Standard Models

Selected topics:

- SUSY & Dark Matter.
- Probing space-time at high energies.

- (“GZK Neutrinos”.)
- (“Top-down” sources of $E > 10^{20}$ eV particles.)
- (Primordial black holes).
- (Cosmic IR radiation).
Dark Matter & SUSY

- Neutralinos can have enhanced density in GC.
- Annihilate to give $\gamma$-rays at GeV and TeV energies.
- Prospects depend strongly on the actual density.

Flux $\sim \left( \frac{\rho}{M_X} \right)^2 \sigma v$
Probing Intergalactic Space-Time

Quantum gravity:

- Discrete space-time “foam”
- Effects propagation of light

AGN Flare
Whipple 1996

- Probe to $M_{\text{plank}} / 100$. 
VHE $\gamma$-ray ASTRONOMY

(A new window)
GeV $\gamma$-ray Sky

- ~ 250 HE point sources, most unidentified.
Pulsars, SNR’s, AGN, Starburst galaxy …

All detected by Cherenkov telescopes.
HE v Sky

Galactic Coordinates

- No sources yet!
GeV and TeV AGN: Blazars

Blazars:
- Powerful, radio-loud objects.
- Highly variable at all wavelengths.
- Jets – superluminal motion.
- Produce GeV/TeV beams.

Mrk 421
Whipple
AGN Variability

- Shortest variations probe to within factor of 10 of the Schwarzschild radius!

\[ R < \frac{cT \delta}{(1+z)} \sim 10^{-4} \text{ pc} \]

\[ \text{For } M = 10^8 M_{\odot}, \quad R_s \sim 10^{-5} \text{ pc}. \]
Correlation with X-rays

- VHE Flares are generally well correlated with X-ray flares.
- But not in this case!
Correlation in $\gamma$-ray and X-ray variability is most easily explained in IC scenarios.

→ Same $e^-$ population.

Additional constraints on electron energies, time scales, etc.

Starting to get a detailed understanding of these sources.
Has DM Already Been Detected?

Probably not!

CANGAROO-II
(S. Australia)

Galactic Center observations with CANGAROO-II telescope

- Observation data
  2001 July (20.3 hours)
  2002 July, August (50.3 hours)
  preliminary result
- 2002 data is under analysis

These excess events indicate gamma-rays from the galactic center
(E > 400GeV)

Tsuchiya et al. 28th ICRC (2003)
More on Dark Matter

- Other good candidates include nearby galaxies with high mass/light: Draco, Ursa Minor, M32, M33.
- These are being pursued.

STAY TUNED!
FUTURE
Future HE Telescopes

In space

- **GLAST, SWIFT**

4 Telescope Arrays

- **VERITAS**
- **MAGIC**
- **ANTARES/NESTOR**
- **HESS**
- **CANGAROO**
- **ANITA**
- **IceCube**

**γ-ray telescopes**

**Neutrino telescopes**
Collaboration: 50 scientists
U.S, Canada, U.K., Ireland

Detector Design:
• Seven 12m telescopes
• 500 pixel cameras (3.5°)
• Site in southern Az (1700m)
• Phase 1 operational in 2006.

Some characteristics:
• Energy threshold ~ 100 GeV
• Ang. Resolution ~ 4 arc-min
• Crab rate ~ 35 \( \gamma/\text{min} \)
  (45s detection!)
VERITAS – Well Underway

Telescope 1:
- All major systems tested.
- Operational in fall 2004.
VERITAS – 1\textsuperscript{st} Cherenkov Images

- End-to-end test of system.
- Looks very good.
VERITAS Event Movie (Dec 03)
Variability Performance

VERITAS:

- has hour-scale sensitivity for time-resolved spectral measurements.
- can probe intrinsic variability timescales.

![Graphs showing variability performance](image-url)
The Competition: HESS

H.E.S.S. Phase I
4 x 12m Telescopes

Namibia Site (1700 m)
GLAST – Satellite Telescope

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

Sky map from 1 year survey

Launch in 2007.
Summary

• Very HE particles provide unique tests of the limits of physical laws. Probe astrophysics in regimes not well understood.

• We have made a survey of the sky at GeV energies. At TeV energies, we have detected some remarkable phenomena, but most of the sky remains unexplored → New Instruments.

• 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)