(Very/Ultra) High Energy Astrophysics
I – Introduction

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- Revolutions in Astronomy
- What is High Energy Astrophysics? The main problematics
- Quick panorama of observations techniques
Revolutions in Astronomy
The Sky in Optical

Gaia's map of 1.7 billion stars in the Milky Way and beyond, © ESA
What shines in Visible Light?

- Thermal emission from hot objects
  - Black-body spectrum
  - Direct relation between temperature and colour
  - Spectroscopic lines (quantum effects – atomic lines)
Ancient Astronomy

- Movement of planets
- Stars & Constellations
- Cosmology centred on Earth
Middle Age

- First instruments (Galileo, 1609)
- Heliocentric system (Copernicus, 1530)
Modern Optical Astronomy

KECK

SALT

HST
Astronomical Objects in Visible – Ancient Astronomy

- Hot objects (stars, nebulae, galaxies)
- Illuminated objects (planets)

Physics:
- Motion (Kepler) → Dark Matter
- Energy Source → Nuclear fusion
- Composition, Mass, Evolution of stars,
- ...

Milky Way in Namibia (H.E.S.S. Telescopes)
First Astronomical Revolution - Radio

- Accidental detection of radio waves from the Galaxy when searching for the sources of interferences in transatlantic communications (Karl Jansky, 1932)
The Sky in Radio

- Radio emission (mostly) from *synchrotron* emission of accelerated electrons in large magnetic fields.
- New classes of objects: radio-galaxies, quasars, …
- First hint of a Violent Universe – High energy Phenomena

Milky Way in Radio

Galactic Centre in Radio

Radio Galaxy 3C296
Radio/optical superposition
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Second Astronomical Revolution – X-Rays

- Originated from the study of the radio waves, reflected by the ionosphere: ionisation attributed by H. Friedman to X-ray emission from the sun
- Observation became possible with rockets (atmosphere opaque to X-rays)
- First detection of a hard X-ray source, Scorpius X-1, 1962
- Many sources quickly detected
The Sky in X-rays (now)

- Superposition of:
  - Thermal emission from hot, compact sources ($\sim 10^6$ K):
    - Neutron stars, pulsars, quasars, …
  - “Non-thermal” emission from high energy particles interacting with interstellar medium (Bremsstrahlung) and magnetic field (Synchrotron)
  - Second hint of a Violent Universe – High energy Phenomena
Third Astronomical Revolution – \( \gamma \)-rays

- \( \gamma \)-rays ideal probes to Very High Energy Universe (only produced in most energetic phenomenon)
- First revolution from space (COS-B, EGRET, Fermi)
- Second revolution from ground (Whipple, CAT, HEGRA → MAGIC, VERITAS, H.E.S.S.)
- See lecture this afternoon
“Cosmic Rays”
Electroscope Discharge

- 1785: Coulomb found that electroscopes spontaneously discharge in air, even insulated
- 1835: Confirmed by Faraday
- 1879: Discharge rate proportional to pressure (Crookes)
  → discharge caused by ionized air

What continuously ionizes the air? High Energy particles from where?
The Cosmic Ray Mystery

1912: Discovery by Victor Hess (Nobel Prize 1936 with Anderson): flux of ionizing particles increases with altitude
1913-1914: Werner Kolhörster repeats and confirms findings of Victor Hess ⇒ 9 km

1928-1929: uses Geiger counters: ⇒ Charged cosmic rays are most probably charged (Science, 1930)
Why do we care?

- Earth constantly bombarded by High Energy Particles from the Cosmos ("Cosmic Rays")

- Numerous implications:
  - Evolution acceleration (genetic mutations)
  - Creation of radioactive isotopes ($^{14}$C)
  - Numerous discoveries in particle physics ($e^+, \mu^+, K^+, \Upsilon, \ldots$)
  - Irradiation of flying crew
  - Probable seed for lightenings
  - Possibly seed for cloud formation
Some major dates – con’t

- 1934: Supernovas proposed as putative sources of CRs. (Baade & Zwicky)
- 1938: Neutron star collapse can be used as cosmological standard candle → cosmology

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**ON SUPER-NOVAE**

**BY W. BAADE AND F. ZWICKY**

Mount Wilson Observatory, Carnegie Institution of Washington and California Institute of Technology, Pasadena

Communicated March 19, 1934
1933: Discovery of positron (e+) in the cosmic rays
⇒ Strong relation with particle physics (μ± (1936), π± (1947), Strange particles (1947), ...)
Discovery of giant showers

- 1939: Discovery of giant showers (Pierre Auger) using coincidence between detectors 50 m apart.
- Up to $10^{15}$ eV (at least)!!

One of the consequences of the extension of the energy spectrum of cosmic rays up to $10^{15}$ ev is that it is actually impossible to imagine a single process able to give to a particle such an energy. It seems much more likely that the charged particles which constitute the primary cosmic radiation acquire their energy along electric fields of a very great extension.
What is high energy astroparticle physics?
Overall picture

Detector on earth

Protons, nuclei

gammas

Electrons

Propagation
- Diffusion
- Energy loss
- Absorption
- Spallation
- Decay
- ...

Cosmic accelerator

Detection

Acceleration

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Cosmic Ray Spectrum

- One wonder of physics
- 12 orders of magnitude in energy, 32 orders in flux → various detection techniques
- Very low spectra at high energy ⇒ huge area needed (>1000 km²)
- Sources unknown
- Isotropically (above 10 GeV)
Open questions

- What are the sources of cosmic rays?

- What are the acceleration mechanisms, what are the accelerated particles?

- Is there new physics in there? (Dark Matter, ...)

- How do high energy particles propagate in Universe? What can we learn from the propagation?

- Link with cosmology: large structure formation, tomography of Universe
The main problematic – I
Particle Acceleration
## Electromagnetic spectrum

<table>
<thead>
<tr>
<th>Energy (eV)</th>
<th>kV</th>
<th>MeV</th>
<th>GeV</th>
<th>TeV</th>
<th>PeV</th>
<th>EeV</th>
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<td>$10^{-6}$</td>
<td>$10^{-3}$</td>
<td>$10^0$</td>
<td>$10^3$</td>
<td>$10^6$</td>
<td>$10^9$</td>
<td>$10^{12}$</td>
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<tr>
<td>$10^{-6}$</td>
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<td>$10^{-9}$</td>
<td>$10^{-12}$</td>
<td>$10^{-15}$</td>
<td>$10^{-18}$</td>
</tr>
</tbody>
</table>

- **Radio**
- **IR**
- **Visible**
- **UV**
- **X rays**
- **\( \gamma \) rays**
- **VHE** (Very High Energy)
- **UHE** (Ultra High Energy)

**Radio**
- Cold objects (10K), Dust...
- Synchrotron emission of accelerated electrons

**IR**
- Hot objects (~2000K), sun, nebula

**Visible**
- Very hot compact objects (~10^6 K), pulsars, black holes...
- Size ~km

**UV**
- Extreme objects, non-thermal processes
  - Particle acceleration in shocks
  - Inverse Compton, Bremstrahlung, Annihilation, Pion disintegration
(Photon) Energy distribution in Universe

- Photon Energy Distribution
  - CMB 3K
  - Galaxies
    (Star light and dust)
  - Compacts objects (X)

- Emitting Power
  - \( P = \sigma \times T^4 \times R^2 \) (Stefan)
  - \( \Rightarrow \) Same power emitted by an object
    10 \times \) hotter and 100 \times \) smaller
  - X-Rays (10 keV): ~1km (Neutron Star) \( \equiv \) Sun
  - VHE (1 GeV): 0.2 nm \( \equiv \) Sun

\( \Rightarrow \) VHE Universe is Non-Thermal

Astroparticle will mainly concern non-thermal Universe
Particle Acceleration

- Intense electromagnetic fields: pulsars (magnetized compact stars in fast rotation)
  \( \sim \) dynamo effect, \( V \sim 10^{12} \) V

- Astrophysical shocks: « ping-pong » particle accelerated at each shock crossing, retro diffused by \( B \)
  (First order Fermi)

- Diffusive acceleration

\[
\frac{\Delta E}{E} = -2 \frac{\vec{v} \cdot \vec{V}}{c^2}
\]

\[
\frac{d N_e}{d E} \propto E^{-2}
\]
The main problematic – II

Propagation
Multi-messenger observations of the Cosmos

- **Photons:** Absorbed by dust and radiation (pair creation on CMB)
- **Protons/nuclei:** Deviated by B field, absorbed by CMB (GZK effect)
- **Neutrinos:** Difficult to detect

⇒ Three “astronomies” possible...
Propagation – Magnetic deflection

- “low energy” charged cosmic rays are deflected by magnetic field and have an isotropic distribution at earth.
- Above $10^{20}$ eV a proton astronomy becomes possible.
GZK cutoff

- 1965: discovery of cosmological background by Penzias & Wilson (CMB)\n  \[ T^\circ = 6 \times 10^{-4} \text{ eV (2.7 Kelvin)} \],\n  \[ N = 400 \text{ cm}^{-3} \]
- Interaction of nuclei with CMB photons \( \Rightarrow \) effet GZK (Greisen, Zatsepin et Kuzmin) (1965)\n  particle degraded to lower energies:\n  \( 10^{22} \) down to \( 10^{20} \) after 100 Mpc

\[
p^+ \gamma_{\text{CMB}} \rightarrow \Delta^+ \begin{cases} \rightarrow p \pi^0 \rightarrow p \gamma \gamma \\ \rightarrow n \pi^+ \rightarrow n \nu_\mu \mu^+ \rightarrow n \nu_\mu \mu^+ \bar{\nu}_\mu \nu_e e^+ \end{cases}
\]
\( \gamma - \text{ray Horizon} \)

- \( \gamma \) -rays absorbed by pair creation on infrared background:
  \[ \gamma + \gamma_{\text{CMB}} \rightarrow e^+ e^- \]

- Limits the size of observable Universe:
  - \( z < 0.1 \) @ 500 GeV
  - \( z < 0.01 \) @ 2 TeV

- Indirect measurement of dust & star background through tomography (energy spectrum vs distance)
  \[ \Rightarrow \text{link with cosmology} \]
Diffusion of particles: high energy particle escape first $\Rightarrow$ Observed spectrum steeper than source spectrum. e.g. $E^{-2.7}$ at earth vs $E^{-2.0}$ at galactic center.

Composition change: spallation (nuclear reaction)
Composition of cosmic rays is altered by propagation!

- Spallation
- Beta decay
- Production of $\gamma$ rays by $\pi^0$ decay
- ....
CR abundances differ from local measurement
- Excess of Li - Be - B et sub Fe
- Secondary nucleus created by spallation ⇒ constraints on propagation
- Primary nuclei (CNO, Fe,..) accelerated in sources
- Other particles are produced in propagation (γ, ν, antiparticles). Excess w/o prediction can be the sign of new physics
The main problematic – III
Detection
Atmospheric Transparency

Ground observation window

Atmospheric transmission reduced by 50%

Indirect detection from ground or high altitude
Acceptance & fluxes

- The higher the energy, the bigger the needed acceptance:
  - 10 GeV: 1 CR/m²/s
    ⇒ 1 m² (satellite or balloon)
  - Knee: 1 CR/m²/an
    ⇒ 1 km² (ground array)
  - Ankle: 1 CR/km²/century
    ⇒ 1000 km² (giant array)
Photons

Coded mask telescope

Space
Photons
High Energy Photons

Anti-coincidence dome
Conversion foils
Tracker
Calorimeter
Pair creation telescope

Space
Very High Energy Photons

From ground

Atmospheric Čerenkov Telescopes

γ Cosmic ray

Electromagnetic shower

Čerenkov light

Very High Energy Photons

1 PeV 100 TeV 10 TeV 1 TeV 100 GeV 10 GeV 1 GeV 100 MeV 10 MeV 1 MeV 100 keV

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ASP V – Windhoek - Namibia - 2018
Charged Particles

Extended air showers – from ground

Ballons

Space

Direct detection

100 EeV  10 EeV  1 EeV  100 PeV  10 PeV  1 PeV  100 TeV  10 TeV  1 TeV  100 GeV  10 GeV
Neutrinos

- Neutrino Scattering off one electron
- Cherenkov emission of the electron in water
Neutrinos

Deep water or ice

Cherenkov Detector
Different Worlds

- Orion Nebula in Optical (left) and Infrared (right)
- Different wavelengths reveal vastly different Universes!