News from the Extreme Energy Cliff!

Angela V. Olinto
The University of Chicago
1912

Victor Hess establishes the cosmic nature of ionizing radiation
Compton: Cosmic Rays = Charged Particles

Millikan: Cosmic Rays = Gamma-rays
Compton:
*Cosmic Rays = Charged Particles*

Millikan:
*Cosmic Rays = Gamma-rays*
Compton: Cosmic Rays = Charged
Extensive Air Showers

1937: Pierre Auger

$\sim 10^{15}$ eV
Ultra High Energy Cosmic Rays

1962 John Linsley
$10^{20}$ eV event
Photon “energy range”
Energy range of Cosmic Rays

+ 12 orders of magnitude
from 0.1 GeV to 0.3 ZeV or from $10^8$ to $10^{20}$ eV
Energies and rates of the cosmic-ray particles

Proton, Helium, heavier nuclei

Gamma-ray $\sim 0.1\%$
Recent Highlights at lower energies
Voyager 1 (Dec. 2012) reached 'the magnetic highway' on its way to interstellar space.
Super-TIGER  (Feb. 2013)
Trans-Iron Galactic Element Recorder
breaks flight duration record: 55 days @ 127,000ft
UltraHeavy Nuclei 10 x sensitivity
study composition and origin of Galactic Cosmic Rays
Alpha Magnetic Spectrometer
(Mar. 2013)

AMS on the ISS announces first results
Alpha Magnetic Spectrometer (Mar. 2013)

AMS on the ISS announces first results
International Space Station

NOW

Japanese Experiment Module (JEM)
Fluxes of Cosmic Rays

- Solar Influence
- Galactic Cosmic Rays
- Extragalactic Cosmic Rays

Energy (eV)
Fluxes of Cosmic Rays by 2015

By 2015

Solar Influence

Galactic Cosmic Rays

Extragalactic Cosmic Rays

Fluxes of Cosmic Rays

Voyager I & II
ACE/CRIS
PAMELA
AMS
CALET
ISS-CREAM
ISS
Balloon
Satellites
Main Open Questions in CR Science

Origin of Galactic Cosmic Rays (GCR):
- What are the accelerators?
- What are they accelerating?
- How do they propagate in the Galaxy?
- Where is the Transition between Galactic & ExtraGalactic CRs?

Origin of ExtraGalactic Cosmic Rays (XGCR):
- What are the accelerators?
- What are they accelerating?
- How do they propagate to Earth?
- At what Energy COSMIC RAY ASTRONOMY begins?

How do Cosmic Rays Affect the Earth and its Biosphere, the Solar System, the Galaxy, other Galaxies, and the formation of Stars and Galaxies?
Questions Related to CR Science

Indirect Dark Matter Searches
- in the Galactic Halo: e+, e-; p, anti-p, γ, ν ... 

Probe of Particle Interactions above LHC energies
- Ultrahigh Energy Cosmic Rays (UHECR) $E_{cm} > 100$ TeV 
- Ultrahigh Energy Neutrinos

Searches for Exotic Components of Matter:
- antinuclei 
- strangelets 
- primordial black holes
Scaled flux $E^{2.5} J(E)$ (m$^{-2}$ s$^{-1}$ sr$^{-1}$ eV$^{1.5}$)

- RHIC (p-p)
- HERA (γ-p)
- Tevatron (p-p)
- 7 TeV 14 TeV LHC (p-p)
- HiRes-MIA
- HiRes I
- HiRes II
- Auger ICRC 2013
- TA SD 2013

- ATIC
- PROTON
- RUNJOB
- KASCADE (QGSJET 01)
- KASCADE (SIBYLL 2.1)
- KASCADE-Grande 2012
- Tibet ASg (SIBYLL 2.1)
Super-novae

Cosmic Rays from Super-novae
Baade & Zwicky (1934)
Supernova Remnants

\[ E^{2.5} \text{ Flux} \left[ \text{m}^{-2} \text{sr}^{-1} \text{s}^{-1} \text{GeV}^{1.5} \right] \]

- SN Rate: \(1/30 \text{ yr}^{-1}\)
- \(\delta = 1/3\)
- \(\gamma + \delta = 2.67\)
- \(H = 4 \text{ kpc}\)

Blasi & Amato 2012
π⁰ decay!

IC 443 & W44

Fermi & AGILE

Ackermann et al (Fermi Collab) ’13
arXiv:1302.3307
Galactic - Extragalactic Transition

KASCADE coll. PHYSICAL REVIEW D 87, 081101(R) (2013)
Large Hadron Collider @ CERN

reaches 14 TeV
$1.4 \times 10^{13}$ eV

27 km or 16.8 mile circumference
Large Hadron Collider

reaches 14 TeV
$1.4 \times 10^{13}$ eV

8.4 Tesla

27 km
to reach $10^{20}$ eV
with LHC magnetic field,
**radius $\sim 10^7$ km** (Sun – Mercury)
or **10 GT** magnets!

8.4 Tesla
Hillas Plot: $E_{\text{max}}$ required

- **neutron star**
- **proton 1020 eV**
- **Fe 1020 eV**
- **LHC**
- **white dwarf**
- **AGN**
- **GRB**
- **SNR**
- **hot spots**
- **IGM shocks**

Kotera & AO ‘11
Inter Galactic Medium
Accretion Shocks
Active Galactic Nuclei (AGN)

\[ L_{\text{bol}} = 10^{43} \text{ erg/s} \quad d = 3.4 \text{ Mpc} \quad L_{\gamma>100\text{MeV}} \approx 10^{41} \text{ erg/s} \]
Current Observatories of Ultrahigh Energy Cosmic Rays

Telescope Array
Utah, USA
(5 country collaboration)
700 km² array
3 fluorescence telescopes

Pierre Auger Observatory
Mendoza, Argentina
(19 country collaboration)
3,000 km² array
4 fluorescence telescopes
Pierre Auger Observatory
Pierre Auger Observatory

Argentina
Australia
Brasil
Bolivia*
Croatia
Czech Rep.
France
Germany
Italy
Mexico
Netherlands
Poland
Portugal
Romania*
Slovenia
Spain
UK
USA
Vietnam*

~ 500 Scientists, 19 Countries
3,000 km² water cherenkov detectors array
4 fluorescence Telescopes
Malargue, Argentina

*Associate Countries
4 times 6 telescopes overlooking the site
$E^3J(E)$ [eV$^2$ km$^{-2}$ sr$^{-1}$ yr$^{-1}$]

$10^{36}$ to $10^{38}$

$130,000$ events!

Normalizations: Hybrid -6%, Inclined +4%, 750 m array +2%, SD -1%

Auger 2013 preliminary
Auger 2013 preliminary

130 000 events!
Off the Extreme Energy Cliff
Auger 2013 preliminary

Normalizations: Hybrid -6%, Inclined +4%, 750 m array +2%, SDL -1%

130 000 events!
3 FD stations overlooking an array of 507 scintillator surface detectors (SD)
Deployment (up to 50/day) 485
2012 CERN Working Group

Unified Spectrum

Energies re-scaled ~10%

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Dawson et al '13
UHECRs Current Status

Leading Observatories: Auger & Telescope Array Agree on the shape of the spectrum
Energy scale: ~10% difference
Off the Extreme Energy Cliff
“Cosmologically Meaningful Termination”

\[ p^+ \gamma_{cmb} \rightarrow \Delta^+ \rightarrow p + \pi^0 \]
\[ \rightarrow n + \pi^+ \]

Proton Horizon
\[ \sim 5 \times 10^{19} \text{ eV} \]

GZK Cutoff
Greisen, Zatsepin, Kuzmin 1966
Greisen-Zatsepin-Kuzmin effect

[Graph showing proton energy loss lengths vs. energy (E [eV])]

- Photo-pion production
- Energy loss length
- Interaction length
- Interaction length, IR
- Pair production
- Cosmological expansion

Kotera & AO 11
Greisen-Zatsepin-Kuzmin effect
Propagation of UHE protons

$\eta(E, z_{\text{max}})$

Modification factor

Spectrum Recovery

Berezinsky, Gazizov, Grigoriev '05
To fit the spectrum, need:
channel spectrum: $E^{-s}$, $E_{max}$
channel composition
Transition Gal/Extragal model
Source evolution: FRII, SFR, uniform

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Kotera, AO '11
Modern Propagation Codes

Public:
CRPropa
1.0 Armengaud et al. ‘06
2.0 Kampert et al. ‘12
3.0 Alvez Batista et al. ‘13
SimProp
Aloisio et al. ‘12

Private:
Allard et al. ‘04
Taylor ‘07
Ahlers ‘10
others...
Modern Propagation Codes

Interaction Cross Sections, z evolution
Background Fields: CMB, UV/Opt/IR
Primary, Secondary nuclei, nucleons,
e+e-, gamma-rays, neutrinos,...
Source Model:
- injection spectrum: $E^{-s}$
- injected composition
- redshift distribution

Propagation Codes

Spectrum

Anisotropies

Composition

Multi-messengers
MANY WAYS TO FIT THE SPECTRUM!

$E^3 \frac{dN}{dE} \left[ \text{eV}^2 \text{m}^{-2} \text{s}^{-1} \text{sr}^{-1} \right]$ vs $\log E \ [\text{eV}]$

+ HiRes I
- Auger

- Dip proton, uniform evol., $s=2.6$
- Dip proton, FRII evol., $s=2.3$
- Dip proton, SFR evol., $s=2.5$
- Galactic mix, SFR evol., $s=2.1$
- Pure iron, SFR evol., $s=2.0$

Kotera, AO 2011
UHECRs Current Status

Leading Observatories: Auger & Telescope Array Agree on the shape of the spectrum
Energy scale: ~10% difference

Composition?
Proton $10^{14}$ eV

$h^{1st} = 17642$ m

hadrons, muons, neutrons, electrs
Composition observable: shower maximum
The figure shows comparisons of theoretical models and experimental data for charged particle interactions. The top left graph plots the average maximum range $X_{max}$ in g/cm² as a function of energy $E$ for protons and iron. The top right graph compares the mean residual energy loss $\sigma(X_{max})$ for protons and iron. The bottom graphs display the log-normal distribution for the different elements: SIBYLL 2.1, EPOS-LHC, and QGSJet II-04.
Auger sees change slope: Change in Composition or interactions

TA: not confirmed yet
Auger sees change slope: Change in Composition or interactions

TA: not confirmed yet

$\langle X_{\text{max}} \rangle$ in the atmosphere

$X_{\text{max}}$ in the detector
GZK
GZK or $E_{\text{max}}$?
GZK vs $E_{\text{max}}$
Specific Source Model
Birth of ultrafast spinning Pulsars
Young Neutron Stars & Magnetars

$M \sim 1 \, M_{\odot}$, $R \sim 10\text{km}$ compact stars
Born Fast spinning ($P \ll 300 \, \text{ms}$)
– slows down due to magnetic breaking (and gravitational radiation early one)
Born $B \sim 10^{12-13} \, \text{G}$

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Blasi, Epstein & AVO ’00, Arons ’03
Birth of ultrafast Pulsars

Newborn Pulsar with: $B_S \equiv 10^{13} B_{13} \, \text{G} \quad Z_{26} \equiv Z/26 \quad \Omega_{3k} \equiv \Omega/3000 \, \text{rad s}^{-1}$

At the light cylinder: $R_{lc} = 10^7 \Omega_{3k}^{-1} \, \text{cm}$ 

$n_{GJ} = 1.7 \times 10^{11} B_{13} \Omega_{3k}^4 / Z \, \text{cm}^{-3}$

Magnetic wind can accelerate particles up to

$E_{\text{max}} = \frac{Z e B_{lc} R_{lc}}{c} \approx 8 \times 10^{20} Z_{26} B_{13} \Omega_{3k}^2 \, \text{eV}$

$E_{cr} = \frac{B_{lc}^2}{8 \pi n_{GJ}}$

$E_{cr} \approx 4 \times 10^{20} Z_{26} B_{13} \Omega_{3k}^2 \, \text{eV}$

The predicted UHECR flux at the Earth is

$F(E) = 10^{-24} \frac{\xi \epsilon Q}{\tau_2 R_{13} E_{20} Z_{26}} \, \text{GeV}^{-1} \, \text{cm}^{-2} \, \text{s}^{-1}$

Maximum Energy? ✔

Spectrum is hard $\sim E^{-1}$

Blasi, Epstein, AVO ‘00
Escape from Supernova Remnant:

- softens the spectrum between protons and iron + pulsar distribution & propagation

Fang, Kotera, AVO '12
Newborn Pulsars fit Spectrum & Auger Composition!

Fang, Kotera, AVO '13
Fast Spinning Newborn Pulsars!

- Flux lower than Galactic pulsars
- ~ 0.3% of normal pulsar pop. for UHECRs

Fang, Kotera, AVO '13
Galactic Cosmic Rays

SN Rate: $\frac{1}{30}$ yr$^{-1}$

$\delta = \frac{1}{3}$

$\gamma + \delta = 2.67$, $H = 4$ kpc

Amato & Blasi '12

Auger–uniform case

Fang, Kotera, AVO '13
Multimessenger Predictions

Observable with IceCube in 2-3 years!

Fang, Kotera, Murase, AVO ‘13
5160 DOMs in 86 strings, depths 1450 m and 2450 m
Neutrino Astronomy Begins

PeV neutrinos first observed by IceCube (Apr’13)

Bert 1.05 PeV

Ernie 1.15 PeV

arXiv:1304.5356
Neutrino Astronomy Begins

PeV neutrinos first observed by IceCube (Apr’13)

Bert 1.05 PeV

Ernie 1.15 PeV

arXiv:1304.5356
Galactic Coordinates

Razzaque '13
IceCube 28 neutrino-like events \( (4.3\sigma) \)

28 events (7 with visible muons, 21 without) on background of \( 10.6^{+4.5}_{-3.9} \) (12.1 ± 3.4 with reference charm model)
IceCube 662 days

Glashow Resonance

E^{-2.3} power law

$\nu_e + \bar{\nu}_e$

$\nu_\tau + \bar{\nu}_\tau$

$\nu_\mu + \bar{\nu}_\mu$

Anchordoqui et al '13
IceCube 28 neutrino-like events (4.3σ)

28 events (7 with visible muons, 21 without) on background of $10.6^{+4.5}_{-3.9} \text{ (12.1 ± 3.4 with reference charm model)}$ Anchordoqui et al ‘13
Galactic CRs?

$E^2 \phi_v [\text{GeV cm}^2 \text{s}^{-1} \text{sr}^{-1}]$

- Frejus $\nu_\mu$
- Frejus $\nu_e$
- SuperK $\nu_\mu$
- AMANDA $\nu_\mu$
- IceCube $\nu_\mu$

- conventional $\nu_\mu$
- conventional $\nu_e$

- prompt $\nu_\mu$ $\nu_e$

- Galactic supernovae

- GRB
- GZK

Events per km$^2$yr

- $100 \rightarrow 10^{-8}$
- $10 \rightarrow 10^{-9}$

Halzen ICRC13
UHECRs Current Status

Leading Observatories: Auger & Telescope Array Agree on the shape of the spectrum
Energy scale: ~10% difference
Composition: controversial

Multi-messenger clues
Cosmogenic (GZK, BZ) Neutrinos & Photons

\[ p + \gamma_{cmb} \rightarrow \Delta^+ \rightarrow p + \pi^0 \rightarrow \gamma \gamma \]
\[ \rightarrow n + \pi^+ \]

\[ n \rightarrow p + e^- + \nu_e \]
\[ \pi^+ \rightarrow \mu^+ + \nu_\mu \]
\[ \mu^+ \rightarrow e^+ + \nu_e + \nu_\mu \]
Highest Energy Neutrino Observatories

IceCube

IceCube Lab

IceTop
80 Strings each with 2 IceTop Cherenkov Detector Tanks
2 Optical Sensors per tank
320 Optical Sensors

2004 Project Starts 1 Hole
2009 Current Status 59 Holes
2011 Projected Completion 86 Holes

IceCube In-Ice Array
86 Strings, 60 Sensors
5160 Optical Sensors

AMANDA-II Array
(Precursor to IceCube)

Deep Core
6 Strings - Optimized for low energy
360 Optical Sensors

Bedrock

ANTARES

ANITA
Next Generation
ARA: Askaryan Radio Array

ARA37

from Vieregg CSS17

ARIANNA
ARIANNA Coll. See arXiv:1207.3846
Greenland Neutrino Observatory (GNO)
Neutrino Detectors

Current Limits

Next Generation

Flux Lower Limit

\[
\log_{10}(E F(E)) \text{ (cm}^{-2} \text{s}^{-1} \text{sr}^{-1})
\]

\[
\log_{10}\text{(energy, eV)}
\]
UHECRs Current Status

Leading Observatories: Auger & Telescope Array Agree on the shape of the spectrum
Energy scale: ~10% difference
Composition: controversial
Multi-messenger clues: not yet

Anisotropies?
Cosmic Magnetic Fields

\[ R_L = \text{kpc} \ Z^{-1} \ (E / \text{EeV}) \ (B / \mu \text{G})^{-1} \]
\[ R_L = \text{Mpc} \ Z^{-1} \ (E / \text{EeV}) \ (B / n \text{G})^{-1} \]

1 EeV = \(10^{18}\) eV

Extra-galactic B?
B < nG

Galactic B deflection
\(<10^\circ\ Z\ (40\ \text{EeV}/E)\)
anisotropic in sky

Halo B?
B \sim \mu \text{G}

Milky way
B \sim \mu \text{G}

\(10\ \text{kpc}\)

weak deflection
E > \(10^{19}\) eV

strong deflection
E < \(10^{18}\) eV
No Galactic Plane Anisotropy

E > 20 EeV Cosmic Rays are EXTRAGALACTIC

Auger Anisotropy limits: rule out Galactic protons to CNO as dominant CR component E > 1 EeV and Fe above 20 EeV

\[ B_0 \in [2 \mu G, 8 \mu G] \]

\[ z_0 \in [2 \text{kpc}, 8 \text{kpc}] \]

Giacinti et al ‘11
Ultrahigh Energy Cosmic Rays

$E > 10^{18}$ eV

= 1 EeV

anole

Extragalactic
Greisen-Zatsepin-Kuzmin effect
Greisen-Zatsepin-Kuzmin effect
Greisen-Zatsepin-Kuzmin effect

![Graph showing proton energy loss lengths versus E (GeV) with annotations for isotropic and anisotropic regions, including energy loss length, interaction length, IR, pair production, and cosmological expansion. Various scales and markers indicate specific energy loss lengths and cosmic distances.]
Where do UHECRs come from?
Auger: consistent with Anisotropy

> 60 EeV

AGN catalog test

28/84 events correlate
Anisotropy Hints > 60 EeV

Auger Observatory

≈ 3 σ pretrial
Telescope Array
Anisotropy Hints > 60 EeV

Soon to be announced!
Anisotropy Hints > 60 EeV

E > 5.7 \times 10^{19} \text{ eV}  \quad \text{20° smoothing}

\approx 5 \sigma \text{ pretrial}

Telescope Array

Auger Observatory

\approx 3 \sigma \text{ pretrial}
Neutrino & UHECR Coincidence
Off the Extreme Energy Cliff
Anisotropy Hints > 60 EeV

Statistically limited
Fluorescence from SPACE

Nadir

Tilt

John Linsley (1925-2002)
JEM-EUSO

Japan, USA, Korea, Mexico, Russia, (Algeria)
Europe: Bulgaria, France, Germany, Italy, Poland, Slovakia, Spain, Switzerland, (Sweden)
13(+2) Countries, 300 researchers
Leading institution: RIKEN
PI: Piergiorgio Picozza
JEM-EUSO Mission

Extreme Universe Space Observatory (EUSO) in the Japanese Experiment Module (JEM) of the International Space Station (ISS)
JEM-EUSO goals

- pioneer the study of EECR from Space
- increase exposure to EECR by 1 order of magnitude
- discover the nearby sources of UHECRs
Payload

System: JAXA

Optics
Rear Fresnel Lens
Precision Fresnel Lens
Iris
Front Fresnel Lens

On-board Calibration
Ground Based Calibration
Ground Support Equipment

Atmospheric Monitoring
Simulation: Worldwide
Focal Surface Detector
Focal Surface Detector

- 4932 MAPMTs (8x8 pixels)
- Elementary Cell (2x2 PMTs = 256 pixels)
- 2.35m
- 55mm
- 167mm

- Focal Surface detector
  - 137 PDMs
  - = 0.3M Pixels

- Photo-Detector Module
  - (3x3 ECs = 2,304 pixels)
  - 1 High Voltage / PDM
Full Sky Coverage
with nearly uniform exposure

Inclination: 51.6°
Height: ~400km
JEM-EUSO
Sky Coverage

Declination [°]

JEM-EUSO (ISS) / 64,000 km²-sr
Auger (φ = 35.5°S) / 7,000 km²-sr
TA (φ = 39.1°N) / 1,800 km²-sr

\[ \text{sin(Declination)} \]
Fluorescence from SPACE

Fast Signal: 50 - 150 μs

- a) Fluorescence
- b) Scattered Cherenkov
- c) Direct (reflected Cherenkov)

Photon types:
- Fluo: 7131
- Dir. Cher.: 568
- Bck. Cher.: 918

10^{20} eV, 60°

1 GTU = 2.5 μs

Background: 500 / m² sr ns
Simulated air shower image on the focal surface detector.

Detected photoelectrons are recorded every Gate Time Unit (GTU) of 2.5 μs continuously.
annual exposure = 10 x Auger
6 $10^4$ km$^2$ sr yr
The EUSO program

1. EUSO-TA:
   Ground detector at Telescope Array site: 2013

2. EUSO-BALLOON:
   3 Balloon flights; 1st from Timmins, Canada 2014
   CNES
   (French Space Agency)
GLS

12 stations:
12 with Xe Flashlamps
6 with Steered Lasers
1 airborne System
PI: P. von Ballmoos
Phase C/D
Flight in Fall 2014
How many UHECRs $> 60$ EeV?

Auger + TA $\sim 30$ events/yr

**JEM-EUSO**

$\sim 200$ events $> 60$ EeV/yr

Earth - surface $\sim 5 \times 10^8$ km$^2$

$\sim 3.4 \times 10^6$ events/yr
How many UHECRs $> 60$ EeV?

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JEM-EUSO
$\sim 200$ events $> 60$ EeV/yr

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Extreme Energy Frontier

Thanks!