Cosmic Ray Astronomy

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What is “Cosmic Ray”? 

- Mainly charged particles: protons (hydrogen nuclei)+helium nuclei+heavier nuclei
- What’s the origin of them?
- What happened during their propagation?
Observing Cosmic Rays

- Direct observation: <100TeV
- Indirect: showers of secondary particles

Pierre Auger Observatory
Observing Cosmic Ray at Ultrahigh Energies

Evolution of the exposures of past, current, and planned UHECR observatories over time, Kotera & Olinto (2011)
Spectrum

broken power-law with cutoff:

- below the **knee** \( (4 \times 10^{15} \text{ eV}) \): \( s = 2.7 \)
- between the knee and **ankle** \( (5 \times 10^{18} \text{ eV}) \): \( s \sim 3 \)
- above the ankle: \( s \sim 2.6 \)

GeV = \( 10^9 \text{ eV} \)
TeV = \( 10^{12} \text{ eV} \)
PeV = \( 10^{15} \text{ eV} \)
EeV = \( 10^{18} \text{ eV} \)
Spectrum

- Greisen-Zatsepin-Kuzmin (GZK) cutoff

  pion production
  \[ p \gamma \rightarrow N + n\pi \]
  \[ E_{p,\pi} \sim 200EeV\left(\frac{\epsilon_{CMB}}{\epsilon}\right) \]

  pair production
  \[ p \gamma \rightarrow p e^+ e^- \]
  \[ E_{p,ee} \sim 0.8EeV\left(\frac{\epsilon_{CMB}}{\epsilon}\right) \]
Explanations for the spectrum

- 1GeV - knee: galactic origin (SNR)
- above ankle: extragalactic origin
- transition right at the ankle?
Why galactic accelerators?

GeV - PeV

• Observation of γ rays disfavor extragalactic regime for the bulk of CRs.

• Guess: transitional regime + knee due to the superstition of cutoffs

• Confirm SNR as a powerful candidate
γ-ray observations indicating SNR origin

Pion bump in the gamma ray emission of SNRs IC 443 and W44 as measured by Fermi-LAT and reported by Ackermann et al (2013).
Why SNR origin

• An energetics point of view:
  
  Observed secondary to primary abundance ratios of galactic cosmic rays: a direct consequence of interaction
  
  \[ L_{cr} \sim 1.5 \times 10^{41} \text{ erg/s} \]

• Power-law distribution from Fermi acceleration
Why SNR origin

- Maximum energy up to the knee in the magnetized plasma

\[
\gamma m_p \frac{dv}{dt} \approx q \frac{v}{c} B \Rightarrow \gamma m_p \frac{v^2}{r_{\text{gyr}}} \approx q \frac{v}{c} B
\]

\(v \approx c: \gamma m_p c^2 \approx q B r\)

\(E_{\text{max}} = \gamma m_p c^2 = 6 \times 10^{15}\) eV \((B \sim 10^{-6}\text{G}, r \sim 1-10\text{pc})\)
Non-linear theory of diffusive shock acceleration (NLDSA)?

- Invoking non-linearity for magnetic amplification: enabling $E_{\text{max}}$ up to the ankle!

- Non-linearity comes from: dynamical reaction of accelerated particles on the shock

  (In more complex cases: coupling between the evolution of the thermal plasma, the CRs, and the magnetic turbulence in the shock vicinity)
Spatially integrated spectral energy distribution of Tycho. The curves show synchrotron emission, thermal electron bremsstrahlung and pion decay as calculated by Morlino and Caprioli (2012)
observations supporting NLDSA in SNR: X-ray rim

Morphology of the Tycho SNR as measured with Chandra (Warren et al, 2005). The three colors refer to emission in the photon energy range 0.95 -1.26 keV (red), 1.63 - 2.26 keV (green), and 4.1 - 6.1 keV (blue). The latter emission is very concentrated in a thin rim and is the result of synchrotron emission of very high energy electrons, indicating magnetic field of ~300μG.
observations supporting NLDSA in SNR: Blamer lines

CR acceleration at SNR shocks: A narrower broad Balmer line and a broader narrow Balmer line

Shape of the Balmer line emission calculated by Morlino et al (2013)
observations supporting NLDSA in SNR: Blamer lines

FWHM of the broad Balmer line as a function of the CR acceleration efficiency for the SNR 0509-67.5, as calculated by Morlino et al (2013b)
NLDSA, the solution for galactic origin CR in PeV - EeV?

NLDSA predicts harder spectrum being concave in shape: at odds with current observations!

- Getting the softer spectrum with the presence of fast moving scattering center around the shock?

- A result of different shock geometry?

Other ways to reach the ankle: different progenitors such as Wolf-Rayet star winds and trans-relativistic supernovae?
Other transition models

- Transition in lower energy
- Ankle: propagation losses due to pair production in proton dominated scenarios

Proton energy loss lengths, Kotera & Olinto (2011)
Other transition models

- Dip model:
  - fit the observed spectrum if the injection is proton dominated

different transitional models compared with data, Kotera & Olinto (2011)
Probing UHECR: composition

$X_{\text{max}}$: the depth in the atmosphere of the shower maximum

- $X_{\text{max}}$ for protons occurs deeper
- proton showers fluctuate more about $X_{\text{max}}$

Black dots presenting measurements from Auger fluorescence detectors (Abraham et al. 2010a). MC simulations from different hadronic interaction models are displayed for primary protons (blue) and primary iron nuclei (red).
Probing UHECR: composition

- knee to 0.1EeV: light primaries to heavier primaries
- 0.1EeV-1EeV: back to light primaries dominating?
- > 10EeV?: high metallically?

Black dots presenting Auger fluorescence detectors (Abraham et al. 2010a). MC simulations from different hadronic interaction models are displayed for primary protons (blue) and primary iron nuclei (red).
The origin of UHECR confirmed by composition measurements

- “top-down” scenario
  
  decay products of more massive particles produced in the early universe: extremely limited by current detections!

- “bottom-up” scenario
  
  extragalactic origin
accelerating mechanism of candidate sources

- Fermi acceleration
  
  GRB shocks, jets and hot spots of AGN, and gravitational accretion shocks.

- Unipolar inductors
  
  Neutron stars

- Others models: magnetic reconnection acceleration, wakefield acceleration, and re-acceleration in sheared jets.
Candidate extragalactic sources

Hillas diagram (1984). Above the blue (red) line protons (iron nuclei) can be confined to a maximum energy of $E_{\text{max}} = 10^{20}\text{ eV}$. The most powerful candidate sources are shown with the uncertainties in their parameters.

$$r_L = \frac{E}{Z e B}$$

$$r_L < R \Rightarrow E_{\text{max}} < z e BR$$
Searching for candidate sources within GZK sphere

- At trans-GZK energies (Above 60 EeV):
  
  only protons and iron survive the propagation over 100 Mpc!

- GZK sphere

Fraction of cosmic rays that survives propagation over a distance > D, for protons above 40, 60, and 100 EeV and for He, CNO, and Fe above 60 EeV. Allard et al. (2007).
Anisotropy discovered in probing candidate sources within GZK sphere

Arrival directions of cosmic rays with energy $E>55$ EeV detected by Auger (black dots) in an Aitoff-Hammer projection of the sky in Galactic coordinates (Abreu et al. 2010). Shaded areas represent a smoothed density map (5 smoothing angle) of the 2MRS galaxies within 200 Mpc over the Auger Observatory field of view.
Magnetic fields causing the lack of astrophysical counterparts?

Expected angular deflection skymap (in degrees) for protons with energy $E \geq 6 \times 10^{19}$ eV, Kotera & Olinto (2011)
In the future: Three pillars and the multi-message approach

• Spectrum+Composition: comparing different transition models in the knee-ankle range

• Anisotropy: probing possible accelerators

• multi-message approach: gamma-ray and neutrinos from PeV to EeV photons and neutrinos at ultrahigh energies
Summary

• The spectrum of cosmic rays:
  
  important features: knee, ankle, cutoff

• Explanation for the spectrum:
  
  solar origin below 1 GeV, SNR origin from GeV to PeV (knee), extragalactic origin above EeV (ankle), GZK cutoff due to pion production in propagation

• What to be revealed in the future:
  
  transition model (ankle transition model VS dip model, through precise measurements of spectrum shape and composition detections)

Accelerators in the extragalactic origin regime
Thanks

Melia section 13.1 on Cosmic Rays