Acceleration of the Ultra High Energy Cosmic Rays to the highest energies

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Overview:

- **Important model restrictions:**
  - Acceleration and astrophysical objects
  - Spectrum and composition. Propagation effects.
  - Anisotropy and source density
  - Secondary gamma-ray and neutrino fluxes

- **Theoretical models:**
  - Extragalactic protons
  - Extragalactic nuclei/mixed composition

- **Conclusions**
Acceleration
**First Order Fermi Shock Acceleration**

The fractional energy gain per shock crossing depends on the velocity jump at the shock. Together with loss processes this leads to a spectrum $E^{-q}$ with $q > 2$ typically.

**Acceleration in electric field nearby from Black Hole or pulsar**

Similar to linear accelerator. Energy spectrum has peak around energy corresponding to potential difference. It can be accompanied by large gamma-ray flux due to energy losses.
Only few classes of astrophysical objects are able to accelerate particles to highest energies.
Spectrum and composition.
Paris, May 17, 2007

supernova remnants
galactic iron, extragalactic protons?
Extragalactic sources, new physics ??

log(FLUX * E^3 in eV^2 m^-2 s^-1 sr^-1)

knee

ankle
toe ?

Akeno 1km²
Tibet
Runjob
Proton Saterite
JACEE

AGASA
Haverah Park
Yakutsk
Stereo Flys Eye
The Greisen-Zatsepin-Kuzmin (GZK) effect

Nucleons can produce pions on the cosmic microwave background

\[ n_{\text{CMB}} = \frac{411}{cm^3} \]

\[ l = \frac{1}{\sigma_{p\gamma} n_{\text{CMB}}} \approx 8 \text{ Mpc} \]

\[ 1 \text{ Mpc} = 3 \cdot 10^{24} cm \]

\[ E_{\text{th}} = \frac{2m_N m_{\pi} + m_{\pi}^2}{4\epsilon} \approx 10^{20} \text{ eV} \]
Pair production by proton

- **Pair production:**
  \[ p + \gamma \rightarrow p + e^+ + e^- \]

- **Cross section:**
  \[ \sigma_{PPP} \sim \alpha \cdot \sigma_T \]
  \[ \sigma_T = \frac{8\pi \alpha^2}{3 m_e^2} = 6.65 \times 10^{-25} \text{ cm}^2 \]

- **Interaction length:**
  \[ l = \frac{1}{\sigma_{PPP} n_{CMB}} \approx 1 \text{ Mpc} \]
Pair production / pion production

- **Pair production losses:**
  \[ R_{PPP} = \frac{1 \text{ Mpc}}{2m_e / M_P} \approx 1000 \text{ Mpc} \]

- **Pion production losses:**
  \[ R_{GZK} = \frac{8 \text{ Mpc}}{m_\pi / M_P} \approx 50 \text{ Mpc} \]

⇒ Sources for \( E > 10^{20} \text{ eV} \) must be in cosmological backyard within 50-100 Mpc from Earth (compare to the Universe size \( \sim 5000 \text{ Mpc} \))
Spectrum of protons

\[ j(E) \propto E^2 \] [arbitrary units]

\[ E \text{ [eV]} \]

- proton
- \( e^+ e^- \)
- \( \pi \)
Horizon for protons

Simulation with SOPHIA, stochastic energy losses, assuming $dE/E = 20\%$ event by event
Fraction of Fe

Simulation by D. Allard
Composition study

T. Pierog, R. Engel and D. Heck, astro-ph/0602190
Composition at energies above $10^{19}$ eV.

- Photons $< 2\%$ (Auger preliminary, ICRC 2007)
- Hadrons $> 98\%$  (Auger)
- Neutrinos 0\% (AGASA, HiRes & Auger)
- Fe $< 50\%$ (AGASA and HiRes)

- Fe/protons impossible to distinguish event by event, contrary to photons and neutrinos.
Arrival directions of UHECR.
AGASA data $E > 4 \times 10^{19}$ eV
~60 events

Clusters -- are events which came from the same part of sky within given (usually small) angle from each other. Angle is 2.5 degrees for AGASA.
Test of AGASA angular cut.

AGASA clustering is by chance with probability $P = 3 \cdot 10^{-3}$.

Finley and Westerhoff, astro-ph/0309159
Arrival directions AGASA and HiRes
Chance probability

D.S., habilitation thesis
Galactic Magnetic field

- At energies $E > 4 \times 10^{19}$ eV proton deflection is only 3-5 degrees.
Proton deflections in extragalactic magnetic field within 105 Mpc from our Galaxy

Extragalactic magnetic field in R=50 Mpc large scale structure box

Dolag et al, 2003

Sigl et al, 2002-2003
Density of UHECR sources from AGASA and HiRes data

M.Kachelriess and D.S., astro-ph/0405258
Small scale clusters: summary

- AGASA sees small scale clusters in arrival directions of cosmic rays at energies $E>4\times10^{19}\text{eV}$ with significance 3 $\sigma$. HiRes data do not contradict to it.
- Galactic magnetic fields are not strong enough to deflect protons at those energies more than for few degrees.
- If extragalactic fields are small, estimate of number of sources agrees with density of AGN.
- Most probable explanation: protons from astrophysical sources. Auger will be able to define source density and probably will find sources.
Clustering on medium scales.
Arrival directions for $E > 40$ EeV in HiRes ($E > 52$ EeV in AGASA)
Probability of correlation

M. Kachelriess and D.S., astro-ph/0512498
Chance probability

M. Kachelriess and D.S., astro-ph/0512498
Medium scale clusters: summary

- At energy $E > 4 \times 10^{19}$ eV (HiRes scale) medium scale clusters show up at 20-25 degrees with significance $\sim 3 \sigma$.

- Galactic magnetic fields are not strong enough to deflect protons at those energies more than for few degrees.

- Those clusters if real should be connected to local Large Scale Structure and extragalactic magnetic fields.

- Most probable explanation: protons and nuclei from sources connected with LSS. Auger will be able to check this but large statistics needed.
Secondary gamma-rays and neutrinos.
Pion production

\[ N + \gamma_b \Rightarrow N' + \sum \pi^i \]
\[ \pi^0 \Rightarrow 2\gamma \]
\[ \pi^\pm \Rightarrow \mu^\pm + \nu_{\mu} \]
\[ \mu^\pm \Rightarrow e^\pm + \bar{\nu}_e + \nu_{\mu} \]
\[ n \Rightarrow p + e^- + \bar{\nu}_e \]

Conclusion: proton, photon and neutrino fluxes are connected in well-defined way. If we know one of them we can predict other ones: \[ E_{\gamma}^{tot} \sim E_{\nu}^{tot} \]
UHECR, gamma-ray and neutrino fluxes

\[
j(E) E^2 \text{ [eV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}]
\]

- EGRET
- GLUE
- MACRO
- Baikal
- AMANDA
- RICE
- Fly’s Eye
- AGASA
- atm \(\nu\)
Sensitivity to fraction of photons

Summary: UHECR photons and neutrinos

- Large fraction of UHECR with energies around GZK cutoff $10^{19}\text{eV} < E < 10^{20}\text{eV}$ most probably are protons from astrophysical sources. Those protons would produce GZK neutrinos + GZK photons.

- GZK photons are $0.01\% - 0.1\%$ fraction of UHECR.

- GZK photons and neutrinos can be tested by future experiments.
UHECR models and standard physics.
UHECR model should solve the following problems:

- Acceleration of charged particles to highest energies $E > 10^{20}$ eV
- Propagation of UHE particles from source to Earth
- Obey composition measurements
- Interaction in atmosphere similar to hadrons
- Large scale isotropy of arrival directions
- Explain small and medium scale clusters
- Obey gamma-ray and neutrino flux limits
- Highest energy cosmic rays should point back to sources
Minimal model of UHECR
Protons from astrophysical sources

- Most of UHECR with $E > 10^{18}$ eV are protons
- Spectrum of single source
- Luminosity of sources and their distribution

Composition HiRes + QGSJet-I

$$F(E) = \theta(E_{\text{max}} - E) / E^\alpha$$

$$n(z) = n_0 \cdot \theta(z_{\text{max}} - z) \cdot \theta(z - z_{\text{min}}) \cdot (1 + z)^{3+m}$$
Protons can fit UHECR data

V. Berezinsky, astro-ph/0509069
Fit of proton spectrum to HiRes-2005 data

additional parameter $E_{\text{fit}} = 2$ EeV

Uniformly distributed sources
Evolution of sources

Z_{min}=0; E_{max}=1.28\times10^{21}

Z_{min}=0.01; E_{max}=1.28\times10^{21}
Mixed composition model

Mix model and pure protons versus composition

Conclusions

- UHECR below GZK cutoff can be explained by standard physics.
- UHECR with energies $E > 10^{20}$ eV if “too many” require new physics or very extreme astrophysics. No big hints so far.
- We are getting close to the predictions of GZK photons and GZK neutrinos, but bigger detectors needed. For neutrinos at least km$^3$, for photons 10*Auger South.
- A lot of astrophysics can be done at $E > 4 \times 10^{19}$ eV: Galactic and extragalactic magnetic fields, sources of UHECR, acceleration mechanism, etc. Probably Pierre Auger Observatory will show interesting results in near future. Bigger detectors needed for detailed study!