UHECR: PROGRESS AND PROBLEMS

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PRODUCTION OF HIGH ENERGY PARTICLES

UHE particles with energies up to $E \sim 10^{20}$ eV can be produced by acceleration (e.g. shock acceleration, unipolar induction, strong electromagnetic waves) and by cosmological relics in particular by Topological Defects and by Superheavy Dark Matter particles. These particles can be observed as UHECR and neutrinos, in some cases as subdominant component.
$E_{\text{max}}$ for non-relativistic jets


$E_{\text{max}}$ from two conditions:

$E_{\text{max}} = Z e B R_s$ (Hillas criterion) and

$B^2 / 8\pi = \omega_{\text{part}}$ or $B^2 / 8\pi \approx L / \pi R_s^2 c \beta$ (equipartition), results in

$$E_{\text{max}} \sim Z e (8L/c)^{1/2} \sim 6 \times 10^{19} Z L_{45}^{1/2} \text{ eV}$$ (1)

Problem: At $\Gamma_j \lesssim 4$ jets are short, and HE protons are absorbed due to $p\gamma$ interaction.
Fanaroff-Riley I and II radio-galaxies
ACCELERATION IN RELATIVISTIC SHOCKS

looks very promising because at reflection a particle obtains $E \sim \Gamma_{sh}^2 E_i$
Illustrative picture

Lab. frame

Problems

Second u → d → u cycle lab. frame

*
Recent progress

Based on PIC simulations (Spitkovsky 2008, Sironi and Spitkovsky 2011) the small-scale microturbulence produced due to self-generated streaming instability results in repeating scattering between upstream and downstream (Fermi process) and in acceleration of particles (see Lemoine and Pelletier 2010 - 2014, Bykov et al 2012, Reville and Bell 2014).

The basic features are as follows:
Streaming instability is produced by interaction of reflected flow of gas with the direct flow. Repeating transition between upstream and downstream is caused by scattering on small-scale microturbulence. Particles are confined to small $\theta \sim 1/\Gamma_{sh}$.

The scale of microturbulence is given by $\lambda \sim c/\omega_{pp}$, where $\omega_{pp} = \sqrt{4\pi ne^2/\gamma m_p}$ is relativistic plasma frequency.

In the recent work by Reville and Bell (2014) the new element was included, the growth-rate time of instability. This rate is found to be very low and it limits strongly $E_{\text{max}}$. 
“The calculated growth-rates (of plasma instability) have insufficient time to modify the scattering, the acceleration to higher energies is ruled out.”

\[ E_{\text{max}} \approx \left( \frac{\Gamma_{\text{sh}}}{100} \right)^2 \left( \frac{\lambda_d}{10 c/\omega_{pp}} \right) \left( \frac{\sigma_d}{10^{-2}} \right) \left( \frac{\sigma_u}{10^{-8}} \right)^{-1/2} \text{PeV} \]

“Ultra-relativistic shocks are disfavoured as sources of high energy particles, in general.”

“.. this paper is not the first to suggest that GRBs are not the sources of UHECRs, but we gone one step further ..”
TOPOLOGICAL DEFECTS

Symmetry breaking in early universe results in phase transitions (D. Kirzhnitz 1972), accompanied by TDs (T. Kibble). Their common feature is production of HE particles.

Ordinary and superconducting strings

Produced at $U(1)$ symmetry breaking.
Particles are massless inside the string and massive outside.
Loop oscillates with periodically produced cusp ($v = c$) and with large Lorentz factors, e.g. above $\Gamma \sim 10^{10}$, at nearby points.
Particles escaping from cusp segment have $E_{\text{max}} \sim \Gamma_c \eta$,
Particles are emitted as jets with $\theta \sim 1/\Gamma_c$.

In a wide class of particle physics strings are superconducting (Witten 1985)

UHE neutrino jets from superconducting strings
V.B., K.Olum, E.Sabancilar and A.Vilenkin 2009

Electric current is generated in magnetic fields ($B$, $f_B$), dominated by clusters.
Clusters of galaxies dominate.
Lorentz factor of cusp $\Gamma_c \sim 1 \times 10^{12}$. $\eta \sim 10^9$ GeV, $E_{\text{max}} \sim 10^{21}$ GeV.

Diffuse neutrino flux:

$$E^2 J_\nu(E) = 2 \times 10^{-8} i_c B_{-6} f_{-3} \text{ GeV cm}^{-2} \text{s}^{-1}$$
UHE NEUTRINOS FROM ORDINARY STRINGS.

1. Ordinary strings with EW Higgs condensate. Vachaspati 2010

Interaction of EW Higgs $\phi$ with the string field $\Phi$ ($\kappa$ is coupling constant):

$$S_{\text{int}} = \kappa \int d^4 x (\Phi^+ \Phi - \eta^2) \phi^+ \phi$$

After GUT symmetry breaking ($<\Phi>=\eta$):

$$S_{\text{int}} = -\kappa \eta \int d^2 \sigma \sqrt{-\gamma} \phi,$$

where $d^2 \sigma$ is string world-sheet space, $\gamma_{ab}$ is the world-sheet metric. The higgses are emitted through the cusp.


$$S_{\text{int}} = (\sqrt{4\pi \alpha/M_{\text{Pl}}}) \int d^4 x \phi T_{\nu}^\nu,$$

$$T_{\nu}^\nu(x) = -2\eta^2 \int d^2 \sigma \sqrt{-\gamma} \delta^4(x^\alpha - x^\alpha(\sigma))$$

is the trace of energy-momentum tensor of string.

Dilatons and moduli are produced as radiation quanta from the cusp. In terms of the Fourier momenta $k$:

$$dN(k) = \alpha^2 G \eta^4 \ell^2/3 k^{-7/3} dk.$$
UHECR: propagation, signatures and mass composition
Total CR spectrum

Energy (eV)  Flux (m$^2$ sr s GeV)$^{-1}$

<table>
<thead>
<tr>
<th>Energy (eV)</th>
<th>Between</th>
</tr>
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<tbody>
<tr>
<td>10^9</td>
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<tr>
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<td>10^{22}</td>
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<tr>
<td>10^{15}</td>
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Knee (1 particle per m$^2$-year)
Ankle (1 particle per km$^2$-year)

2nd knee
Spectrum and Features
Signatures of particle propagation through CMB and EBL

\[ E_{eq1} = 2.4 \times 10^{18} \, \text{eV}, \quad E_{eq2} = 6.1 \times 10^{19} \, \text{eV} \]

Pair-production dip and GZK cutoff.

\[ \tau_{A}^\text{ebl} (\Gamma_c) = \tau_{A}^\text{cmb} (\Gamma_c) \]

We want to see **observational signatures of interaction**, but in our calculations **model-dependent quantities** also appear, such as **distances** between sources, their cosmological **evolution**, modes of **propagation** (from rectilinear to diffusion), local source **overdensity** or **deficit** etc.

Energy spectrum in terms of **modification factor** characterizes well the **interaction signatures**.
MODIFICATION FACTOR

\[ \eta(E') = \frac{J_p(E)}{J_p^{\text{unm}}(E')} \]

where \( J_p^{\text{unm}}(E) = KE^{-\gamma_g} \) includes only adiabatic energy losses.

Since many physical phenomena in numerator and denominator compensate or cancel each other, dip in terms of modification factor is less model-dependent than \( J_p(E) \).

It depends very weakly on:

- \( \gamma_g \) and \( E_{\text{max}} \),
- modes of propagation (rect or diff),
- large-scale source inhomogeneity,
- source separation within 1-50 Mpc,
- local source overdensity or deficit,..

It is modified by presence of nuclei (\( \gtrsim 15\% \)).

Experimental modification factor:

\[ \eta_{\text{exp}}(E) = \frac{J_{\text{obs}}(E)}{KE^{-\gamma_g}} \].
Comparison of pair-production dip with observations

\[ \gamma_g = 2.7 \]

- Akeno-AGASA
- HiRes I - HiRes II
- Yakutsk

\[ \text{modification factor} = 2.7 \]

\[ \text{E, eV} \]

\[ \text{modification factor} \]

\[ \eta_{\text{total}} \]

\[ \eta_{ee} \]
GZK CUTOFF IN HiRes DIFFERENTIAL SPECTRUM

$\gamma_g = 2.7$

$E, \text{eV}$

$\eta_{\text{total}}$

$\eta_{ee}$
$E_{1/2}$ in HiRes integral spectrum confirms that steepening in the differential spectrum is the GZK cutoff:

$$E_{1/2}^{\text{meas}} = 10^{19.73 \pm 0.07} \text{ eV} \quad \text{cf} \quad E_{1/2}^{\text{theor}} = 10^{19.72} \text{ eV}$$
DIRECT MEASUREMENTS OF MASS COMPOSITION

is a necessary component of consistent picture
The Fluorescence detector measures the longitudinal shower profiles
MASS COMPOSITION: HIRES (top) vs AUGER (bottom)
Interpretation of Auger spectrum and mass composition
Aloisio, V.B., Blasi (2013), see also Taylor, Ahlers, Aharonian (2012).

\[ \gamma_g = 1.0, \ E_{\text{max}} = 5Z \text{ EeV} \]

\[ \gamma_g (p, He) = 2.7 \]
Impact of KASCADE-Grande experiment

‘Small’ 700 × 700 m² array with scintillation and muon detectors. p+He component is separated by muon content with properties:

- p+He component at 0.1 - 1.0 EeV separated as ’electron-rich’ using special event criteria, 6300 events.
- extragalactic, otherwise anisotropy at $E \sim 1$ EeV.
- flat spectrum $\gamma = 2.79 \pm 0.08$, cf $\gamma = 3.24 \pm 0.08$ for total.
CONCLUSIONS

- UHECR are characterised by high $E_{\text{max}}$ (the highest energy observed is $3 \times 10^{20}$ eV) and by propagation signatures in energy spectrum.

- The propagation signatures for protons are pair-production dip (due to $p + \gamma_{\text{cmb}} \rightarrow p + e^+ + e^-$) and GZK cutoff (due to $p + \gamma_{\text{cmb}} \rightarrow N + \pi$).

- The propagation signature for nuclei is GR cutoff with $\Gamma_c \approx (3 - 4) \times 10^9$ for all nuclei, and $E_{\text{GR}} \approx A\Gamma_c m_N \approx (3 - 4)A \times 10^{18}$ eV, if $E_{\text{GR}} < E_{\text{acc max}}$.

- HiRes and TA observed proton dominance in the direct measurements of the mass composition and signatures of proton interaction with CMB: pair-production dip and GZK cutoff in differential and integral spectra.
• **Auger** reports the nuclei composition steadily heavier with increasing energy. The models which explain simultaneously the Auger energy spectrum, $X_{\text{max}}(E)$ and RMS (dispersion) must have very flat generation spectrum $\gamma_g < 1.6$ and additional EeV proton+He component with steep spectrum.

• The main problem of UHECR at present is contradiction between HiRes/TA and PAO data on mass composition at $E > (3 - 5)$ EeV.

• **From Auger data there must be the sources at distance 60 - 80 Mpc** *(Taylor, Ahlers, Aharonian 2011)* and the detection of these sources in the future experiments may solve the UHECR puzzle.