Astroparticle Physics: Puzzles and Discoveries

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September 11, 2007
Formula of astrophysical discoveries:

ALL GREATEST DISCOVERIES IN ASTROPHYSICS APPEARED UNPREDICTABLY AS PUZZLES.

WHAT WAS PREDICTED WAS NOT DISCOVERED.
# Astrophysical Puzzles and Discoveries

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Greatness of False Discoveries
Cygnus X-3

VHE (≥ 1 TeV) and UHE (≥ 0.1—1 PeV) “gamma” radiation from Cyg X-3 was observed in 80s by many detectors: Kiel, Haverah Park, Fly’s Eye, Akeno, Baksan, Tien-Shan, Ooty, Gulmarg, Plateu Rosa, Crimea, Dugway, Whipple …

Underground muon signal was also detected: NUSEX, Soudan, MUTRON

In 1990-1991 CASA and CYGNUS put upper limits, which excluded early observations.

Impact on theoretical astroparticle physics:
- High energy astrophysics with new particles: production, detection and general limits.
- Acceleration in binary systems.
UHE COSMIC RAY PUZZLE
Undiscovered Greisen-Zatsepin-Kuzmin (GZK) cutoff (1966)

\[ p + \gamma_{\text{CMB}} \rightarrow N + \pi \]

\( \Gamma_p \varepsilon_{\text{CMB}} \sim 140 \text{ MeV}, \)

\( E_{\text{GZK}} \sim (3 - 5) \times 10^{19} \text{ eV} \)

No viable astrophysical solution to 'AGASA excess' was found
SOLUTIONS WITH NEW PHYSICS
motivated by AGASA excess at \( E \geq 1 \times 10^{20} \text{ eV} \)

- **SUPERHEAVY DARK MATTER** \((X \rightarrow \text{hadrons})\)
  \[ M_X > 10^{12} \text{ GeV}, \quad \tau_X > 10^{10} \text{ yr} \]

  No radically new physics involved, *fits the data*

- **RESONANT NEUTRINOS (Z-BURSTS)**
  \[ \nu + \bar{\nu}_{DM} \rightarrow Z^0 \rightarrow \text{hadrons} \]

  Excluded: too high flux of neutrinos required

- **TOPOLOGICAL DEFECTS**
  Reliable physics, weak GZK cutoff, disfavoured.

- **NEW PARTICLES**
  Strongly interacting neutrino, light (quasi)stable hadron
  (e.g. glueballino \( \bar{g}g \)), mirror neutrons: not excluded.

- **LORENTZ INVARIANCE VIOLATION**
  Most radical proposal: *fits the data.*
MEASURED FLUXES OF UHECR
Propagation of protons through CMB in intergalactic space leaves the imprints in the spectrum in the form of the dip (due to $p + \gamma_{\text{CMB}} \rightarrow p + e^+ + e^-$) and GZK cutoff (due to $p + \gamma_{\text{CMB}} \rightarrow N + \pi$).

These features are convenient to analyze with help of modification factor

$$\eta(E) = \frac{J_p(E)}{J_p^{\text{unm}}(E)}$$

Here $J_p(E)$ includes total energy losses and $J_p^{\text{unm}}(E)$ only adiabatic energy losses (redshift).
Dip and GZK Steepening in Diffuse Spectrum

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

1: \( \gamma_g = 2.7 \)
2: \( \gamma_g = 2.0 \)

modification factor

E, eV

\[ 10^{17}, 10^{18}, 10^{19}, 10^{20}, 10^{21} \]
Dip in Comparison with Akeno-AGASA Data

\[ \gamma_g = 2.7 \]
Dip in Comparison with HiRes Data

HiRes I - HiRes II

$\gamma_g = 2.7$
Dip in Comparison with YAKUTSK Data

\[ \gamma_g = 2.7 \]
Dip in Comparison with Auger 2007 Data

\[ \eta_{ee} \]

\[ \gamma_g = 2.6 \]

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

\[ E, \text{ eV} \]

\[ \log_{10} \text{ modification factor} \]
GZK Cutoff in HiRes Data

In the integral spectrum GZK cutoff is numerically characterized by energy $E_{1/2}$ where the calculated spectrum $J(>E)$ becomes half of power-law extrapolation spectrum $KE^{-\gamma}$ at low energies. As calculations (V.B.&Grigorieva 1988) show

$$E_{1/2} = 10^{19.72} \text{ eV}$$

valid for a wide range of generation indices from 2.1 to 2.8. HiRes obtained:

$$E_{1/2} = 10^{19.73\pm0.07} \text{ eV}$$
COSMOLOGICAL PUZZLES
IN THE PAST AND PRESENT
The expanding Friedmann solution of the Einstein equation has horizon and flatness problems.

**Horizon problem**

CMB decouples from matter after recombination ($z_{\text{rec}} \approx 1100$, $t_{\text{rec}} \approx 1.2 \times 10^{13}$ s). The regions separated by the horizon size $ct_{\text{rec}}$ are seen at angle $\Theta \approx (1 + z_{\text{rec}})ct_{\text{rec}}/ct_0$.

They cannot have equal temperatures, and CMB cannot be isotropic on the scale $\Theta > 2^\circ$.

**Flatness problem**

Why universe is flat now?

Within Friedmann regime because of initial condition at $t_{\text{Pl}} \sim 1/m_{\text{Pl}}$.

To have $\Omega -1 \sim O(1)$ now it is necessary to have $\Omega -1 \sim \xi$ at $\xi \sim 10^{-30}$. 
**Inflation as a Solution**

A. Guth, K. Sato, A. Linde, P. Steinhardt

Einstein equation and energy conservation result in equations

\[
\dot{a}^2(t) = \frac{8\pi}{3} Ga^2(t) \rho \\
\ddot{a}(t) = \frac{4\pi}{3} G(3\rho + p)a(t) \\
\dot{\rho} = -3H(p + \rho)
\]

For matter with equation of state \( p = -\rho \) and \( \rho = \rho_0 \) realized e.g. for scalar field \( \varphi \) rolling down in flat potential

\[
a(t) = a_0 e^{H_0 t}
\]

with

\[
H_0^2 = \frac{8\pi}{3} G\rho_0
\]

an initial bubble expands exponentially and it solves the problem of horizon and flatness.

- The whole universe is produced from one causally connected bubble
- \( 1 - \Omega \sim \exp(-Ht) \) provides \( \Omega = 1 \) at all \( t \). At the end of inflation \( 1 - \Omega = \varepsilon \) with \( \varepsilon \) exponentially small.
Where Is Dark Matter and Why Is There Dark Energy?
**WMAP-07** $\Lambda$CDM best fit:

\[ H_0 = 73.2 \text{ km/s Mpc} , \ \Omega_{\text{tot}} = 1 + \Omega_k , \ \Omega_k = -0.011 \pm 0.012 \]
\[ \Omega_b = 0.0416 , \ \Omega_m = 0.238 , \ \Omega_\Lambda = 0.716 \]

**Indirect evidence for DM**

- $\Omega_m >> \Omega_b$ (**WMAP**: height of 3d peak is too low without DM)
- Virial mass in galaxies $M_{\text{vir}} >> M_b$
- Theory of LSS formation (hierarchical clustering model)

**Direct search for DM**

- Observation of modulation signal by **DAMA**

**Alternative explanation**

- Modified theory of gravitation at low acceleration $a < a_0 \sim 10^8 \text{ cm}^2/\text{s}$ (**MOND**)
Three gravity fields: $g_{\mu\nu}, U_\mu, \varphi$

One non-dynamical field: $\sigma$

Two dimensional constants: $G$ and $l$

Two dimensionless constants: $k$ and $K$

$l$ and $K$ define the critical acceleration $a_0$

As asymptotic TeVeS gives general relativity and Newtonian gravitation and at $a < a_0$ MOND

This theory successfully describes (with baryonic matter only): flat rotation curves, high velocities in clusters and lensing. Recently Dodelson et al 2006 have demonstrated that galaxy formation can be also explained.

However:
If $\Omega_{CDM} = 0$ the third acoustic peak in WMAP would be much lower than observed.
Bullet Cluster 1E0657-558

Weak lensing and X-ray observation
Gravitational potential is not centered by X-ray emitting plasma, which is dominant baryon component ($M_{\text{gas}}/M_{\text{gal}} \sim 5 - 7$).
**Accelerated Expansion of the Universe**

*Einstein* equation

\[ R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = -8\pi GT_{\mu\nu} + \Lambda g_{\mu\nu} \]

\[ = -8\pi G(T_{\mu\nu} - \rho_{\text{vac}}g_{\mu\nu}) \]

l.h.s. is represented by geometry, r.h.s. by energy density of matter or gravitating fields.

Accelerated expansion can be obtained due to r.h.s. terms as \(\Lambda\) and by dark energy fluid in \(T_{\mu\nu}\),

or

by modification of l.h.s. (i.e. gravity equation).

Priority should be given to lambda term. **WMAP** data are analyzed in terms of \(\Lambda\)CDM model.

The best fit:

\(h = 0.73, \quad \Omega_{\text{tot}} = 1.0, \quad \Omega_b = 0.042, \quad \Omega_m = 0.24, \quad \Omega_\Lambda = 0.72\).
Lambda term was introduced first by Einstein, who later took back his proposal. This is a pity. Otherwise he could become famous.”

Rocky Kolb.
$\Lambda$-term describes the time-invariable vacuum energy $\rho_{\text{vac}}$. It corresponds to the equation of state $p = -\rho$ and $\rho = \rho_{\text{vac}} = \text{const}$.

When density of matter $\rho_m(t)$ in the expanding universe falls down below $\rho_{\text{vac}}$, universe expands exponentially like in case of inflation

$$a(t) = a_0 \exp(H_0 t)$$
Vacuum-Energy Problem

$\Lambda$-term implies vacuum energy

$$\rho_\Lambda = \Lambda / 8\pi G = \Omega_\Lambda \rho_c = 4 \times 10^{-47} \text{ GeV}^4 \quad \text{(for} \ \Omega_\Lambda = 0.73)$$

$\rho_\Lambda$ could be given by energy density of some exotic field(s) $\sigma$ plus zero-modes of all known particles $i$. Taking them as quantum oscillators with ground–state energy $\omega/2$, one obtains

$$\rho_\Lambda = \rho_\sigma + \sum_i \rho_{\text{vac}}^{(i)} \quad (1)$$

For example, reliably known quark-gluon condensate energy

$$\rho_{\text{vac}}^{\text{QCD}} \approx 0.03 \text{ GeV}^4$$

is 45 orders of magnitude larger than $\rho_\Lambda$ (Dolgov).

(1) needs unnatural compensation to very small (or zero) value of $\rho_\Lambda$. This is very general problem for all kinds of vacuum energy.
ACCELERATED EXPANSION: MODELS
\[ R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = -8\pi G \left( T_{\mu\nu} - \rho_{\text{vac}} g_{\mu\nu} \right) \]

Acceleration is described by:

1. Vacuum energy $\rho_\Lambda g_{\mu\nu}$ ($\Lambda$-term); equation of state $p = \omega \rho$ with $\omega = -1$ and $\rho = \text{const.}$
2. DE fluid in $T_{\mu\nu}$ term; equation of state $p = \omega \rho$ with $\omega < -1/3$.

   It can be realized as:
   - ultra-light scalar field rolling down the potential field (quintessence) *Wetterich 1988, Peebles & Vilenkin 1999*
   - phantom (ghost field) with $\omega < -1$; K-essence, *Chaplygin gas* etc.

   Observational data *WMAP + SNLS + ($\Omega_{\text{tot}} = 1$):*
   \[ \omega = -0.967 \pm 0.07 \] favor $\Lambda$-term.

3. Modified gravity: modification of l.h.s. (no DE!)
   e.g. *Dvali et al 2000* brane model.
**Acceleration and Anthropic Approach**

Why does acceleration start now?
Why $\Lambda$-term is zero or very small?
Why physical parameters are tuned to produce life, e.g. $\text{^3He}^4 \Rightarrow \text{^6C}^{12}$ resonance?

These questions might have answers not in terms of physical principles, but because in a universe with “wrong” parameters there is nobody to measure them.
From Inflation to Anthropic Principle

Chaotic inflation naturally results in infinite number of universes.
Inflaton field $\varphi$ with chaotic initial conditions results in self-regeneration process of inflation in different parts of unlimited (superhorizon) space. This process does not have beginning and continues without end.

There are at least two versions of this process: eternal inflation and quantum tunneling (creation of universes from nothing), or quantum fluctuations (space-time foam).

The values of $\varphi$ and $\rho_{\text{vac}}$ have different values in different universes with distribution $W(\rho_{\text{vac}})$. It may be peaked at $\rho_{\text{vac}} = 0$ or not, but observer exists only when $\rho_{\text{vac}}$ is small enough or zero.
“In my book “Many worlds in one” I have written that in one of the infinite number of universes Elvis Presley is alive and continues singing his songs. Since that time my mailbox is overfilled: the Elvis’ fans are asking me to forward a letter to him”.

A. Vilenkin
CONCLUSIONS
From three puzzles existing until recently in astroparticle physics:

Where is GZK cutoff?
Where is dark matter?
Why $\rho_{\text{vac}}$ is very small or zero?

we have answered to the first two:

- Interaction of protons with CMB is seen as a dip and beginning of GZK cutoff in the UHECR spectrum. HiRes confirms numerically the existence of GZK cutoff.

- The second problem most probably does not exist at all. DM is not seen in directly-search experiments either because sensitivity is still low or because DM particles are superweakly interacting (e.g. gravitino or SHDM particles).

MOND and TeVeS should be considered as interesting alternatives.
Problem of $\rho_{\text{vac}} = 0$ or very small ($\sim 10^{-47}$ GeV$^4$) is the most serious puzzle of modern physics, but it could be a problem of elementary-particle physics, which predicts the zero-mode energy too high for cosmology. The most reliable case is

$$\rho_{\text{vac}}^{QCD} \approx 0.03 \text{ GeV}^4$$

Compensation in

$$\rho_\Lambda = \rho_\sigma + \sum_i \rho_{\text{vac}}^{(i)}$$

is unnatural and can be found now only in the framework of anthropic theories of many universes.
Is Nature Natural or Friendly?

V. Rubakov

Anthropic theory is one of the friendly solutions in physics.
Thank you!
Dip in Comparison with Data

Akeno-AGASA

HiRes I - HiRes II

Yakutsk

Auger
Energy Calibration by Dip

Energy shift $E \rightarrow \lambda E$ for each experiment independently to reach minimum of $\chi^2$ in comparison with theoretical curve $\eta(E)$.

AGASA $\lambda_{\text{AG}} = 0.9$
HiRes $\lambda_{\text{Hi}} = 1.20$
Yakutsk $\lambda_{\text{Ya}} = 0.75$
AGASA and HiRes spectra calibrated by the dip. The energy shift needed for $\chi^2_{\text{min}}$ is $\lambda_{\text{AGASA}} = 0.9$ and $\lambda_{\text{HiRes}} = 1.2$. Both are allowed by systematic errors.
AGASA and Yakutsk spectra calibrated by the dip. The energy shift needed for \( \chi^2_{\text{min}} \) is \( \lambda_{\text{AGASA}} = 0.9 \) and \( \lambda_{\text{Yakutsk}} = 0.75 \). Both are allowed by systematic errors.
AGASA-HIRES-YAKUTSK DISCREPANCY

AGASA, Hires and Yakutsk spectra calibrated by the dip.
COMPARISON OF AUGER WITH CALIBRATED DATA
COMPARISON OF AUGER WITH CALIBRATED DATA
RE-EVALUATED AGASA SPECTRUM (2006)

Phenomenologically re-evaluation comes from two effects:

(i) **Aperture** (from MC simulation)
\[ A_{\text{old}} = \text{const down to } 4 \times 10^{18} \text{ eV}, \quad A_{\text{new}}(E) \text{ at } E \leq 1 \times 10^{19} \text{ eV}. \]

(ii) **Energy evaluation** by the Hillas formulae.

\[ E = a \times 10^{17} S_{600}^b \text{ eV} \]

\[ a_{\text{old}} = 2.21, \quad b_{\text{old}} = 1.03. \]

\[ a_{\text{new}} = 1.89, \quad b_{\text{new}} = 1.01. \]

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<tr>
<th>( E_{\text{new}} ) (eV)</th>
<th>( 3 \times 10^{18} )</th>
<th>( 1 \times 10^{19} )</th>
<th>( 3 \times 10^{19} )</th>
<th>( 1 \times 10^{20} )</th>
<th>( 2 \times 10^{20} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E_{\text{new}} / E_{\text{old}} )</td>
<td>0.809</td>
<td>0.790</td>
<td>0.773</td>
<td>0.754</td>
<td>0.744</td>
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RE-ANALYSED AGASA DATA (2006)

AGASA data corrected by the new aperture (left panel) and AGASA data with new aperture shifted by $\lambda_A = 0.88$ (right panel).
AGASA and YAKUTSK DATA before and after ENERGY SHIFT
THE DIP and ANKLE TRANSITIONS

In the dip model transition occurs at $E_{tr} < E_b = 1 \times 10^{18}$ eV, i.e. at second knee. This transition agrees perfectly with the standard galactic model.

In the ankle model transition occurs at $E_\alpha = 1 \times 10^{19}$ eV and the galactic flux at this energy is half of the total in contradiction with standard galactic model.
Abell 520
CL 0024+17