A possibility of interpretation of the cosmic ray knee near 10 TV as a contribution of a single close source

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ISCRA-2019, June 27
The NUCLEON space experiment:
A new universal cosmic-ray knee near the magnetic rigidity 10 TV

Statistical significance > 3.9σ in all nuclear groups (4.2σ-4.4σ - the last data)

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10TV-knee transforms to ~50GeV knee in usual terms of E/particle (HAWC, NUCLEON)
The simplest possible explanation of 10 TV-knee:

10TV is a limit of acceleration of some kind of CR source - a single nearby one (?) or generic (?)

Argument No 1 for a single source:

The knee is very sharp to be from multiple sources
Argument No 2 for a single source:

The chemical composition is approximately constant around the knee

Is it actually possible to fit the data by a single reasonable CR source?
General problem formulation

CR diffusion equation:

\[ \frac{\partial N(R, t, r)}{\partial t} - \nabla [D(R)\nabla N(R, t, r)] = Q(R, t, r) \]

\[ D(R) = D_0 \left( \frac{R}{R_{ref}} \right)^{-\delta} \]

“Flash lamp” approximation:

\[ F_Z(R, r, T) = \frac{C}{4\pi} G(R, T, r)Q_Z(R) \]

\[ F_Z(R, r, t) \] – local flux
\[ G(R, t, r) \] – Green function
\[ R \] – rigidity,
\[ r \] – the distance to the source,
\[ t \] – age of the source
Green’s function

Spectrum and Anisotropy of Cosmic Rays at TeV-PeV-energies and Contribution of Nearby Sources

Classical Green’s function in 3d space:

\[
G(R, r, T) = \left[ \frac{1}{4\pi D(R)T} \right]^{3/2} e^{-\frac{r^2}{4D(R)T}}
\]

G (r = 0.3kpc, T = 30 ky)

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Spectrum and chemical composition of the source

Example parameters:
\( \gamma = 2 \)
\( \Delta \gamma = 2 \)
\( \omega = 3 \)

\[
Q_z = \frac{C}{4\pi} Z_i \times \text{NormalCoefficient} \times R^{-\gamma} \left( 1 + \left( \frac{R}{R_{\text{ref}}} \right)^{\omega} \right)^{-d \gamma/\omega}
\]

\[
\text{NormalCoefficient} = \frac{W k}{\int_{10^9}^{\infty} R \times R^{-\gamma} \left( 1 + \left( \frac{R}{R_{\text{ref}}} \right)^{\omega} \right)^{(-d \gamma/\omega)} dR \times \sum_{i=1}^{28} (Z_i A_{bi})}
\]
A single source model:
Background + knee in the “Flash lamp” approximation

Flux, rel.un.

Power-law background

10-TV-knee

Background - from ATIC and CREAM

Superposition of diffusion Green functions with the primary E-spectrum for some distance time, and SN energy.
Multivariable fit

Minimized function:

\[
\chi^2 = \sum_{Z=1,2,6,8} \sum_i \left\{ \frac{F_i^Z - M_i^Z(T, r, W, H_e, C_r, O_r)}{\sigma_i^Z} \right\}^2
\]

\(W\) - SN explosion energy (erg), CR fraction \(k = 0.1\);
\(H_e = I_p / I_{He}\) etc;
\(i\) – number of point in the spectrum

In every point of the phase space (\(T < 20 \text{ ky, } r < 1 \text{ kpc}\)) this function is minimized for free parameters \(W, H_e, C_r, O_r\)
\(\{40 < \log W < 60\}, \{0 < H_e < 1\}, \{0 < C_r < 1\}, \{0 < O_r < 1\}\)

In total 45 experimental points are being fitted in 4D phase space of free parameters for each point of \(\{T, r\}\) space.
$\chi^2$ of the approximation

Reasonable values:
$T \sim 5$ ky
$R \sim 0.3$ kpc
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He/H ratio in the source
Reasonable values:
$T \sim 5 \text{ ky}$
$R \sim 0.3 \text{ kpc}$
Possible source existence region

Reasonable values:
T \sim 5 \text{ ky}
R \sim 0.3 \text{ kpc}
The best fit:
$T = 3$ ky, $L = 0.3$ kpc, $W = 1.6 \times 10^{51}$ erg (10% in the cosmic rays)
All nuclei groups are fitted by the same single source separately.

A fit of a knee by a reasonable single source is possible!
Lupus Loop:

$L = 0.15 - 0.5\text{ kpc}$

$T = 15 - 30\text{ ky}$
Lupus Loop
HB9 - Good real candidate

D. A. Leahy and W. W. Tian

L = 0.4 – 1.2 kpc
T = 4 – 7 ky
Conclusions

● A fit of a 10TV-knee by a reasonable single source is possible.

● There are several of SNR candidates to fit 10TV-knee.

● There may be several SNR that are invisible to us
Further development of the model

- Inclusion of EAS experiments (VERITAS, HAWC) to get a better fit for the source
- Transition from the “flash lamp” approximation to models with source spectrum dependence on age of the SNR
- Inclusion of gamma astronomy data to construct source models
Back ups
Point-like source contribution age dependence

Distance $r = 0.1$ kpc

Flux, rel.un.

$r = 0.1$ kpc

$10$ ky

$1$ ky

$0.1$ ky

$R(GV)$