Title: Very High Energy Astrophysics

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Aim of this study:

- The summary of the observation and the acceleration of cosmic-ray particles with energies from 10^{12} eV to the end of the energy spectrum (more than 10^{20} eV).
- The prediction of the change of the chemical composition at the knee region via modeling the particle motion in the Galactic magnetic field.

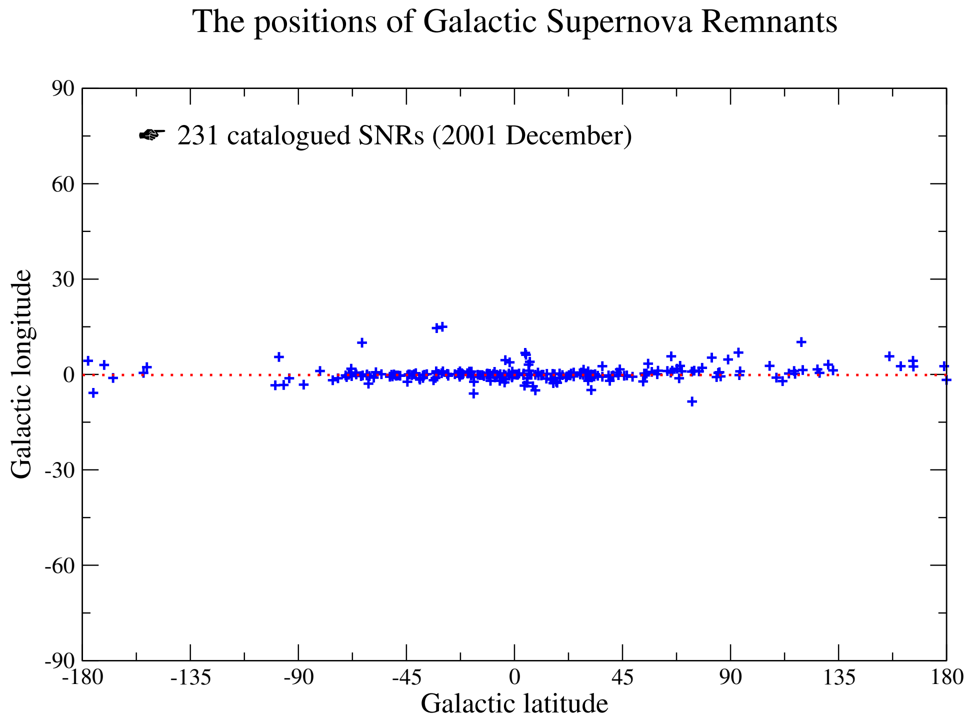
Procedure of the work:

- distribution of initial particles in the Galaxy
- initial composition and stability of particles in the cosmic ray flux
- modelling the motion of cosmic rays in the Galactic magnetic field
- the escape of different nuclei from the Galaxy
- the comparison between results of my simulations and experimental data

Cosmic rays come from supernova explosions

(The particles are accelerated in SN remnants by 1st order Fermi acceleration, maximum achievable energy is 10^{15} eV.)

- The power of CRs is similar to the energy of supernova explosions.
- Shock-accelerated particles have spectral index $\sim$2, propagation of cosmic rays ~ 2.7.
- The isotropy of arriving CRs (many nearby sources, magnetic fields).
- SNRs are sources of GeV and TeV gamma rays (photo-pion production).



(Green, 2001)

<u>**Table of elements at 1 TeV**</u> (Wiebel, 1994)

Element	Z	%	Group
H	1	42.26	**low 42 %**
He	2	25.57	**26 %**
Li	3	0.82	**medium**
Be	4	0.19	
B	5	0.34	
C	6	4.18	
N	7	0.93	
O	8	6.19	**13 %**
F	9	0.13	
Ne	10	1.81	**high**
Na	11	0.30	
Mg	12	3.16	
Al	13	0.45	
Si	14	2.76	**9 %**
P	15	0.11	
S	16	0.86	
Cl	17	0.12	**very high**
Ar	18	0.32	
K	19	0.21	
Ca	20	0.57	
Sc	21	0.12	
Ti	22	0.45	
V	23	0.25	
Cr	24	0.54	
Mn	25	0.53	
Fe	26	7.02	**10 %**
Co	27	0.03	
Ni	28	0.39	

- The summary of many experiments.
- No influence of the Sun above 10^{10} eV.
- No significant escapes from the Galaxy.

Particle's motion

The first step is to model the trajectories of charged particles through any magnetic field. The equation of motion is

$$\vec{a} = \frac{q}{m}(\vec{v} \times \vec{B}) = \frac{Zc^2}{E[\mathrm{eV}]}(\vec{v} \times \vec{B}).$$

Where q, Z, m and $\vec{v}$ are the particle's charge ($q = Ze$), proton number, mass and velocity (almost equal to the velocity of light in vacuum), E particle's energy in eV, $\vec{B}$ is the magnetic field.

For complicated magnetic field solved by numerical method: 4th-order Runge-Kutta routine with adaptive step size control.

Galactic magnetic field

Regular: Bisymmetric spiral configuration with dipole character (BSS-A model) in cylindrical coordinates (Han & Qiao, 1994):

$$B_\theta = B_0(r) \cos\left(\theta - \beta \ln \frac{r}{r_0}\right) \cos p$$
$$B_r = B_0(r) \cos\left(\theta - \beta \ln \frac{r}{r_0}\right) \sin p$$

where $B_0 = 3\frac{R_0}{r}$, for $r < 4$ kpc $B_0 = 6.4\mu G$.

Above and under the Galactic plane (Stanev, 1997):

$$B(r, \theta, z) = B_0(r) \cos\left(\theta - \beta \ln \frac{r}{r_0}\right) \exp(-z/z_0)$$

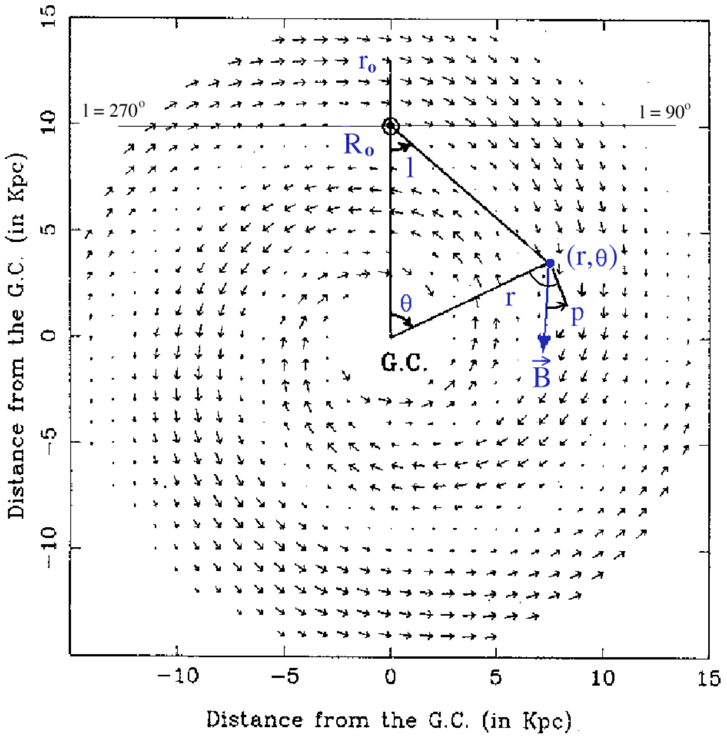
Magnetic field is in μG (1 G = 10^{-4} T).

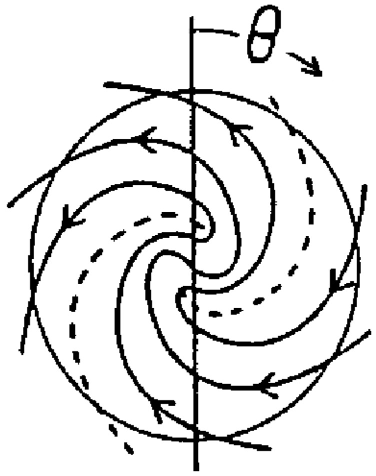
Constants: $R_0 = 8.5$ kpc; $r_0 = 10.55$ kpc; $p = -10°$; $\beta = \frac{1}{\tan p} = -5.67$; for $|z| < 0.5$ kpc is $z_0 = 1$ kpc and for $z_0 = 4$ kpc for $|z| > 0.5$ kpc

Random: The random orientation and strength of irregular magnetic field ($B_{ran} < \sqrt{3} \times 10^{-9}$ T) were generated in cells of size L_0 and random position.

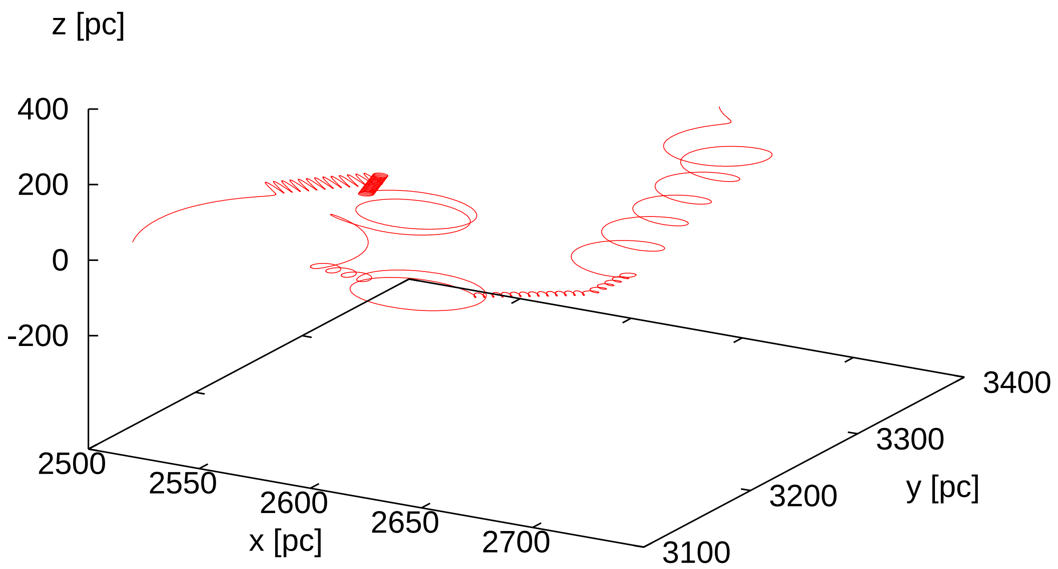
The total magnetic field: $\vec{B}_{tot} = \vec{B}_{reg} + \vec{B}_{ran}$

Regular galactic magnetic field

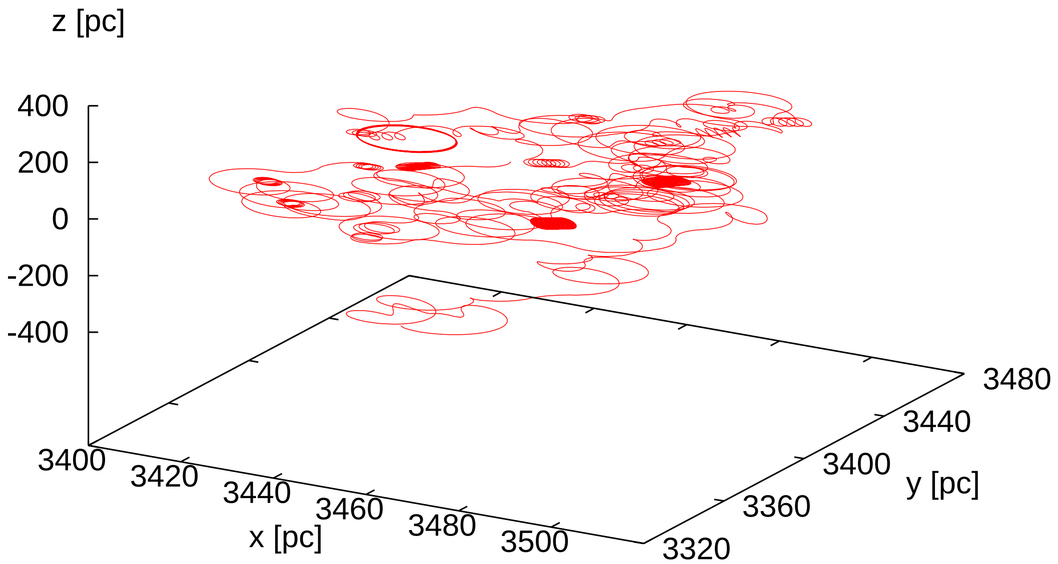




Trajectory of iron nucleous with 10e18 eV after 10e12 s (Lo=50pc, 20%).

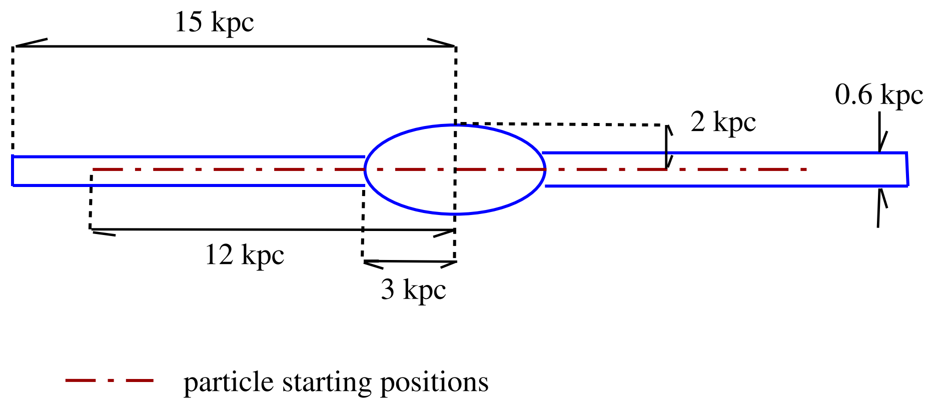


Trajectory of iron nucleous with 10e18 eV after 10e12 s (Lo=10pc, 20%).



The introduction to the results

- The boundary of the Galaxy:



- The chemical composition of cosmic rays:

$$< \ln A >= \frac{\sum_i n_i(\ln A_i)}{\sum_i n_i}$$

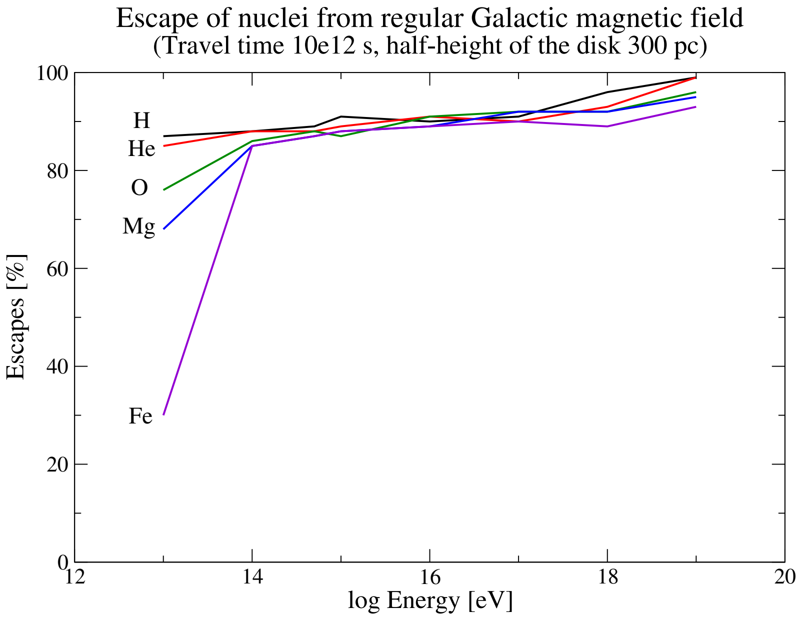
(n_i denotes the weight of element i with mass number A_i).

The values of the mean logarithmic mass <ln A> for the elements which were used in our modelling are presented in Table.

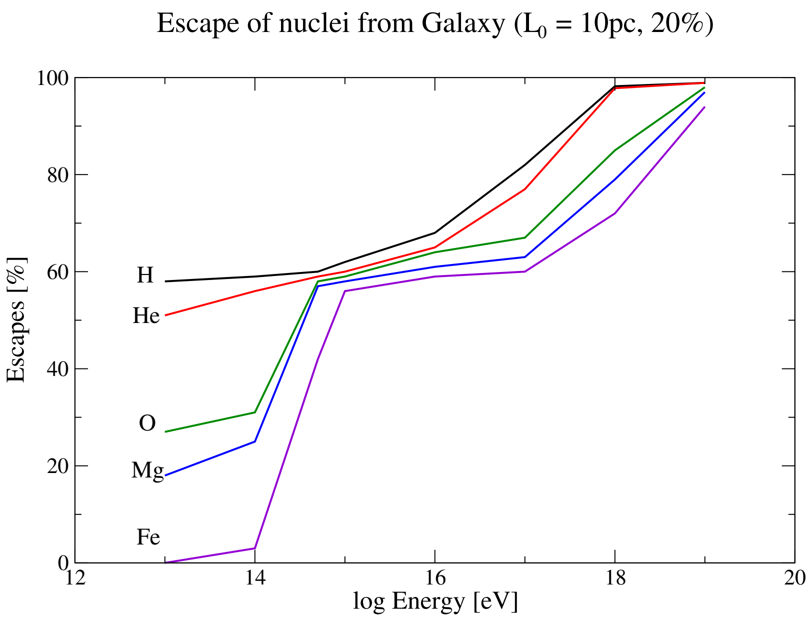
${}^{A}_{Z}X$	${}^{1}_{1}H$	${}^{4}_{2}He$	${}^{16}_{8}O$	${}^{24}_{12}Mg$	${}^{56}_{26}Fe$
<ln A>	0	1.39	2.77	3.18	4.03

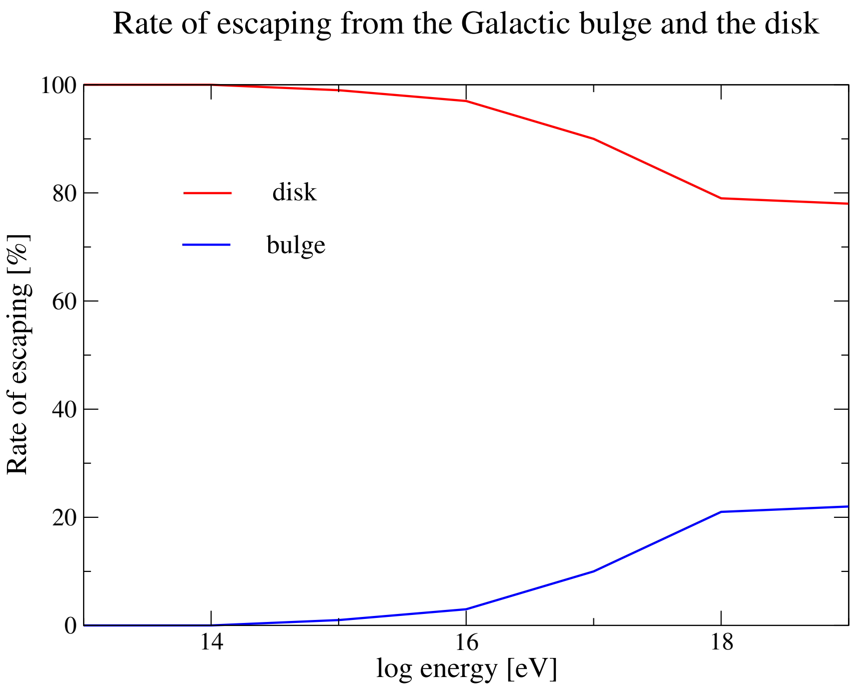
The results of the modelling

- Escape from regular GMF:

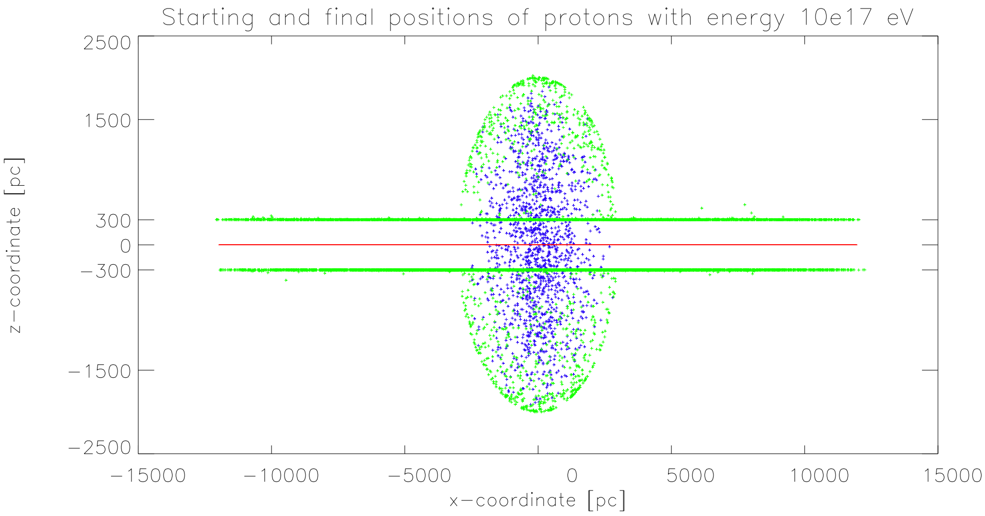


- Escape from regular GMF with random components:





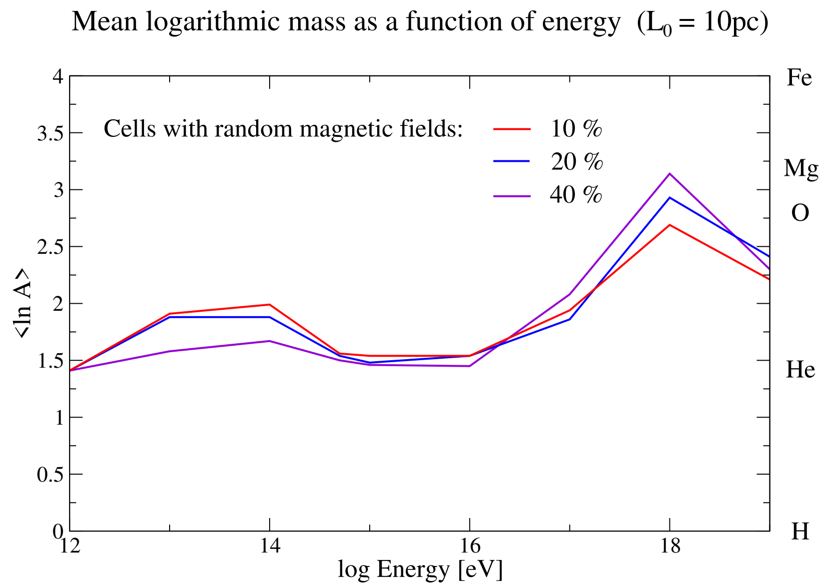
The rate of proton escape from the Galactic bulge and disk as a function of the energy. The size of cells was 10 pc and 20% of cells were with random magnetic field.



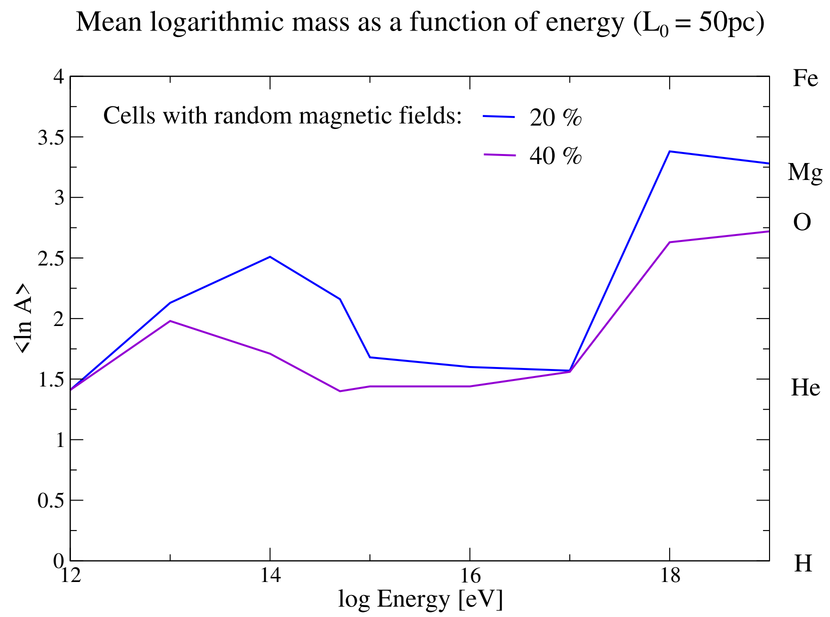
The red line indicates starting position (10,000 particles), green dots show exit points and blue dots the final position of non-escaping particles.

The chemical composition of cosmic rays

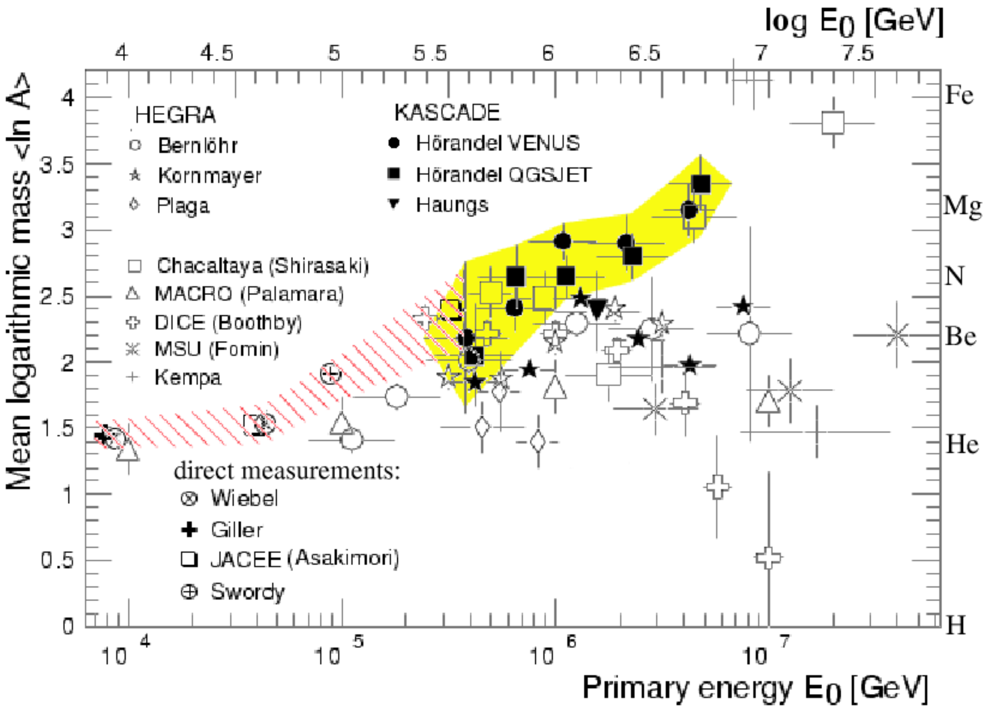
- The size of the cells L_0=10 pc.



- The size of the cells L_0=50 pc.



The results of the experiments



The drawbacks of assumptions

- Below 10^{15} eV the propagation must be solved by more realistic method (for example diffusion models).
- The effects of energy losses and gains in the interactions with the interstellar matter have to be included.
- We can expect more type of sources in Galactic and extra-galactic space resulting in more complicated composition of cosmic-ray flux.
- The magnetic field of halo was ignored.

The main results of my modelling

- The lighter particles escape faster from the Galaxy.
- The constant value of the escape of all nuclei in the energy range $(5 \div 100) \times 10^{14}$ eV is caused by the geometrical boundaries of the Galactic disk and the bulge.
- The nuclei escaping above 10^{16} eV is caused mainly by random component of GMF.
- For higher number of the cells with random magnetic field the nuclei escape is slower for both tested size of the cells.
- More particles escaped from the Galaxy when the size of the cells was 50 pc, than it was 10 pc.

We can summarize that

- The influence of the Galactic magnetic field on the motion and chemical composition of cosmic rays was tested.
- We have found that for energies above 10^{16} eV, where our model is sufficient to describe the motion of nuclei, we can expect an increase of the mean logarithmic mass, under assumption that the Galactic sources will have the same characteristics which were used in our model.

My thanks go out to all people who helped me with this work.