On the inverse problem for extragalactic cosmic ray nuclei with energies 10^{18} to 10^{20} eV

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The transport equation for protons and nuclei in the expanding Universe

$$-H(z)(1+z)\frac{\partial}{\partial z}\left(\frac{F(A,\varepsilon,z)}{(1+z)^3}\right) -$$

$$-\frac{\partial}{\partial\varepsilon}\left(\varepsilon\left(\frac{H(z)}{(1+z)^3}+\frac{1}{\tau(A,\varepsilon,z)}\right)F(A,\varepsilon,z)\right)+\nu(A,\varepsilon,z)F(A,\varepsilon,z)$$

$$=\sum_{i=1,2\ldots}\nu(A+i\to A,\varepsilon,z)F(A+i,\varepsilon,z)+q(A,\varepsilon)(1+z)^m.$$

$$H(z)=H_0((1+z)^3\Omega_m+\Omega_\Lambda)^{1/2}$$

The Hubble constant

$$\varepsilon = E/A$$

The energy per nucleon

The solution is expressed in terms of the Green's function

$$F(A,\varepsilon,z=0)=\sum_{A'}\int d\varepsilon' G(A,\varepsilon;A',\varepsilon')q(A',\varepsilon').$$

$$N(E)=\sum_{A,A'}A^{-1}\int d\varepsilon' G(A,E/A;A',\varepsilon')q(A',\varepsilon').$$

The observed spectrum on the total energy of particles

$$q(A,\varepsilon)=k(A)Q(\varepsilon A/Z)$$

We assume that the spectra of nuclei are functions of rigidity

$$N_i=\sum_j S_{ij}Q_j,\quad S_{ij}=\sum_{A,A'}\frac{Z(A')k(A')}{A'A}G(A,E_i/A;A',\varepsilon_j Z/A)\Delta\varepsilon_j$$

It is possible to invert the problem and to find the sources from the observed spectra

Solution of the ill-posed problem

$$L = \sum_i \left(1 - \frac{1}{N_i} \sum_j S_{ij} Q_j \right)^2 + \varepsilon_R \sum_j \left(Q_{j-1} - 2Q_j + Q_{j+1} \right)^2$$

ε_R - Regularization parameter

$$\sum_j S_{kj}^R Q_j = N_k^R, \quad N_k^R = \sum_i \frac{1}{N_i} S_{ik},$$

$$S_{kj}^R = \sum_i \frac{1}{N_i^2} S_{ik} S_{ij} + \varepsilon_R \left(6\delta_{kj} - 4\delta_{k,j-1} - 4\delta_{k,j+1} + \delta_{k,j-2} + \delta_{k,j+2} \right)$$

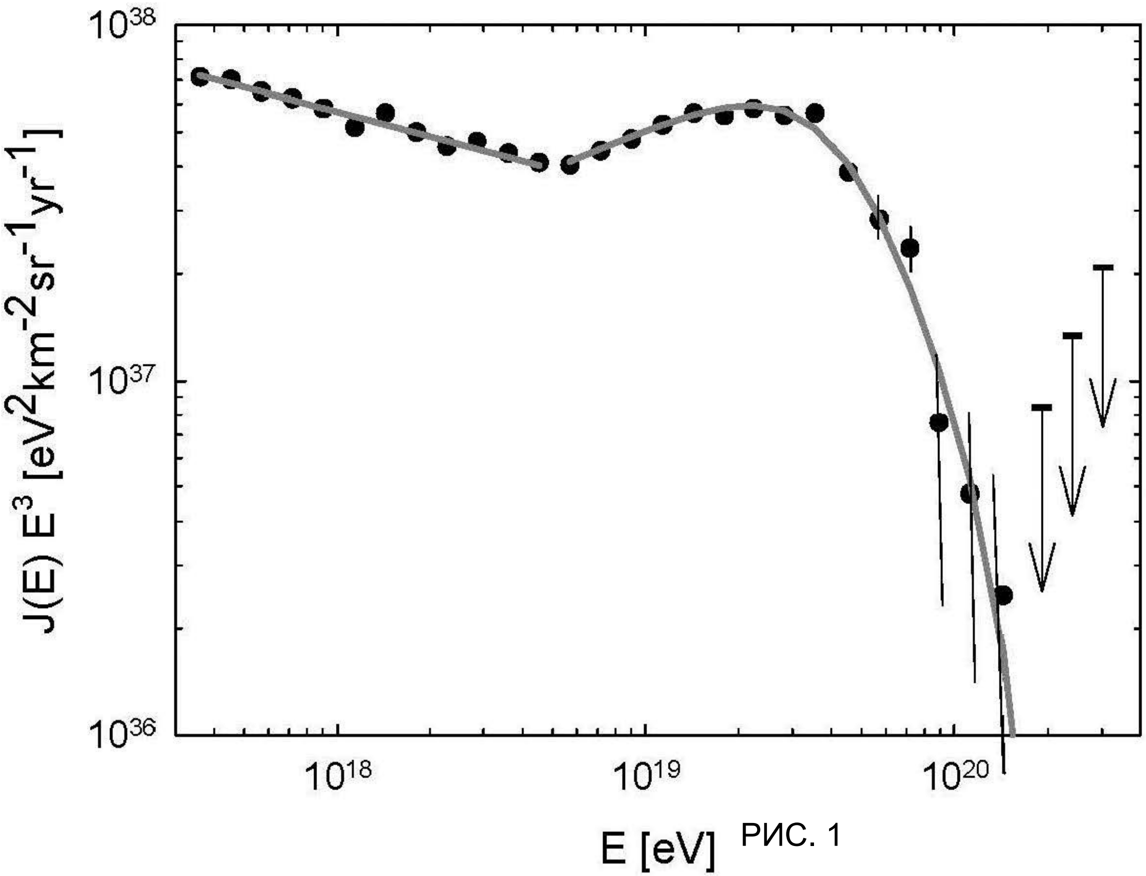


РИС. 1

Analytical approx. of Auger spectra

$$E_{ankle} = 5 \cdot 10^{18}\ \text{eV},\ E_{1/2} = 10^{19.63}\ \text{eV},\ E_c = 1.5 \cdot 10^{20}\ \text{eV}$$

$$J(E) \propto E^{-3.23},\ E < E_{ankle};$$

$$J(E) \propto E^{-2.63}\left(1 + \exp\left(\frac{\log(E / E_{1/2})}{0.15}\right)\right)^{-1} \exp\left(-E^4 / E_c^4\right),\ E > E_{ankle}$$

The composition of the cosmic rays in the sources. Table 1. *k(A)* .

	1 H	4 He	12 C	16 O	24 Mg	28Si	56Fe
Solid line	1	0.2	0.03	0.03	0.015	0.004	0.004
Dashed line	1	6	0.65	0.2	0.096	0.12	0.015

Similar to Galactic CRs

A factor of 10-30 heavier than Galactic CRs

Fig. 2. Results for the composition of the sources given in the second row of Table 1. The spectra of cosmic rays on the Earth after propagation in the intergalactic medium are shown.

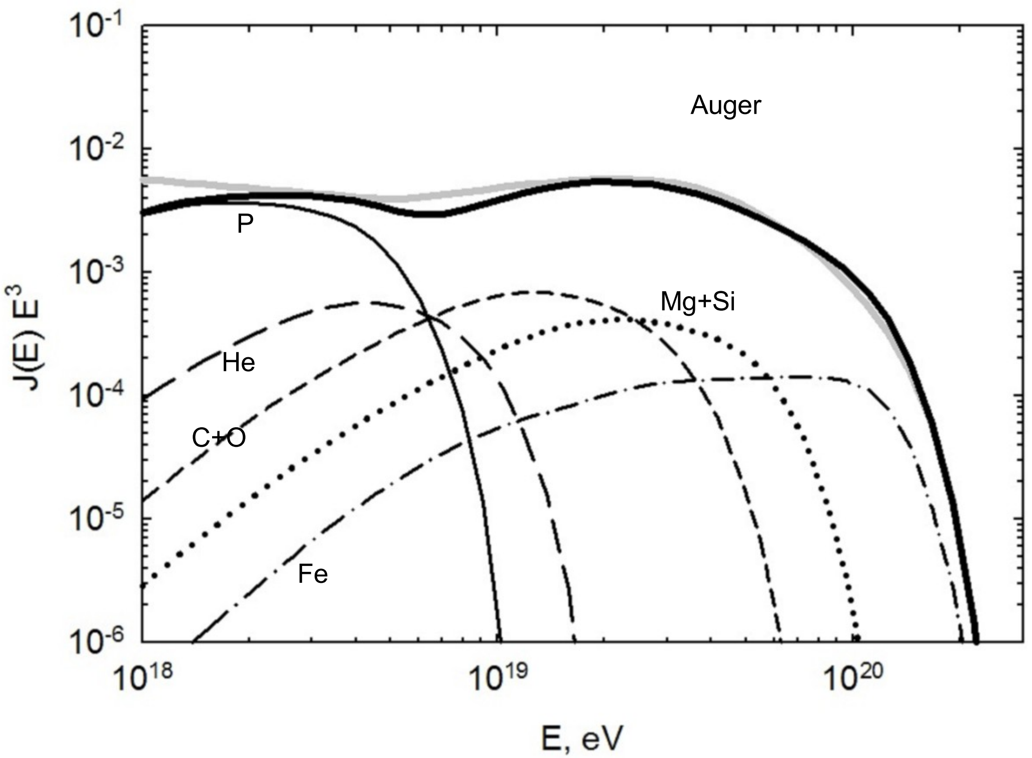


Fig.3. Results for the composition of the sources given in the third row of Table 1. The spectra of cosmic rays on the Earth after propagation in the intergalactic medium are shown.

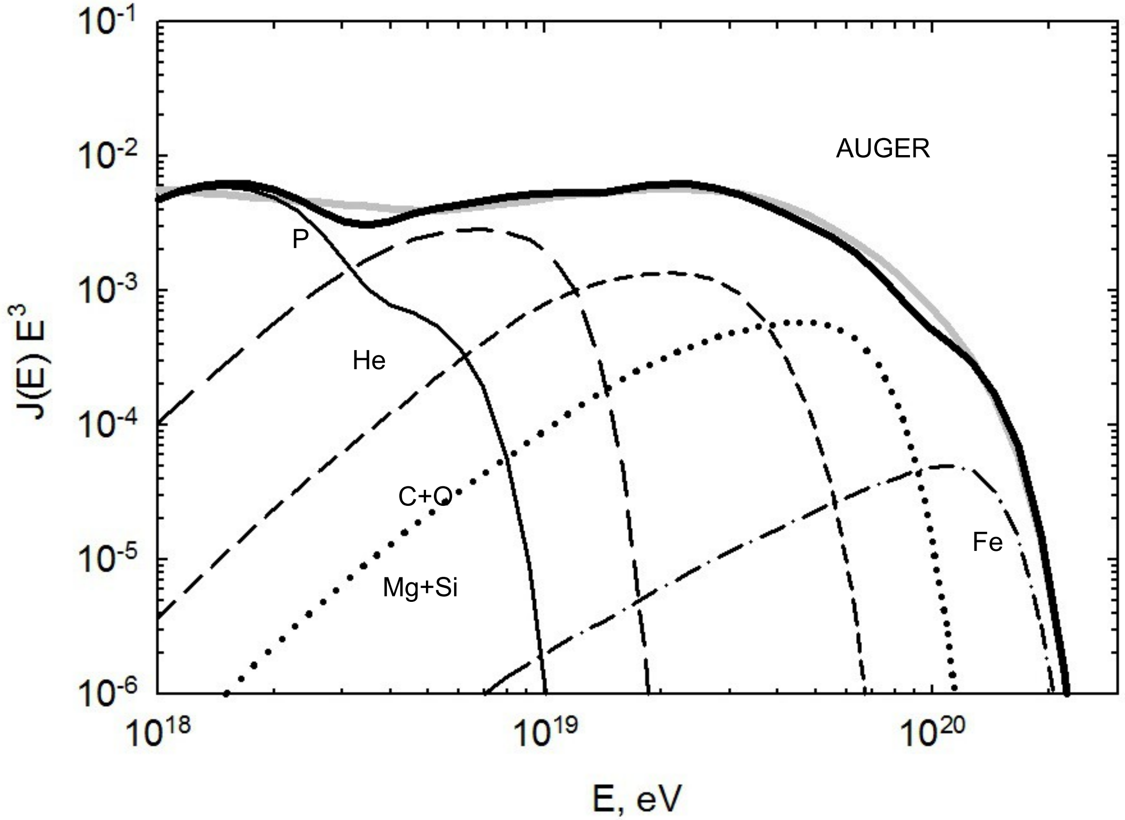
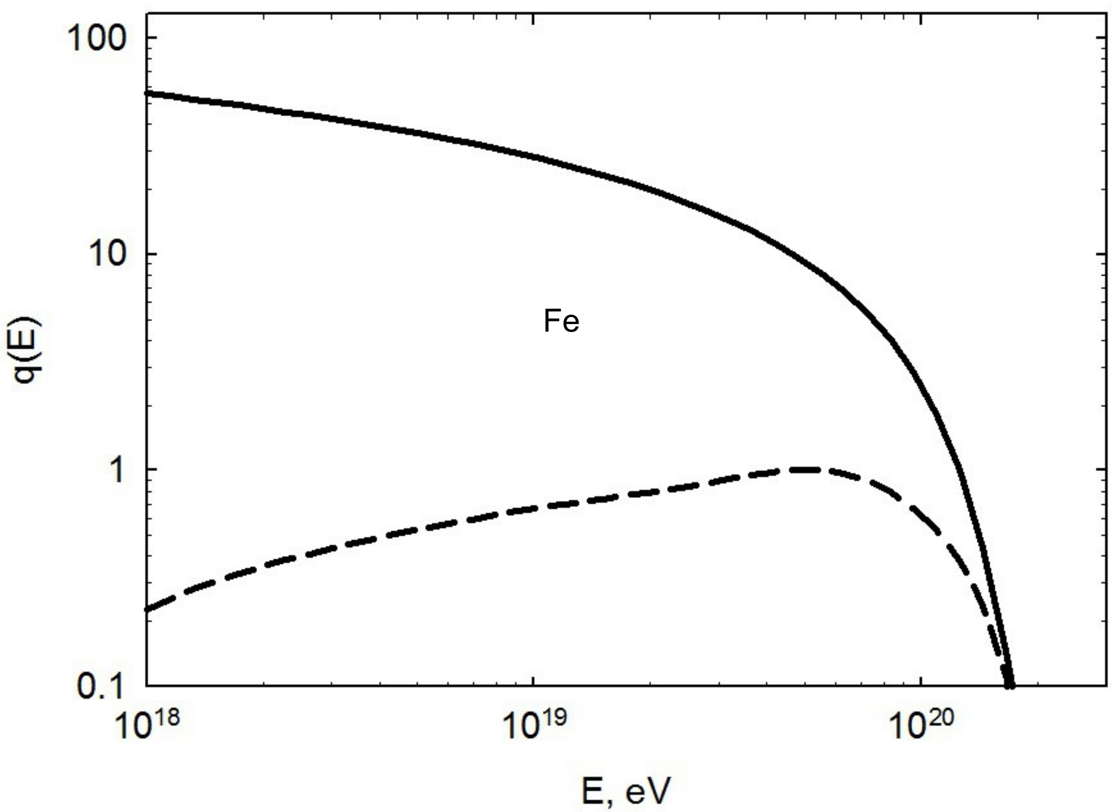


Fig.4. The calculated spectra of iron nuclei in extragalactic sources.



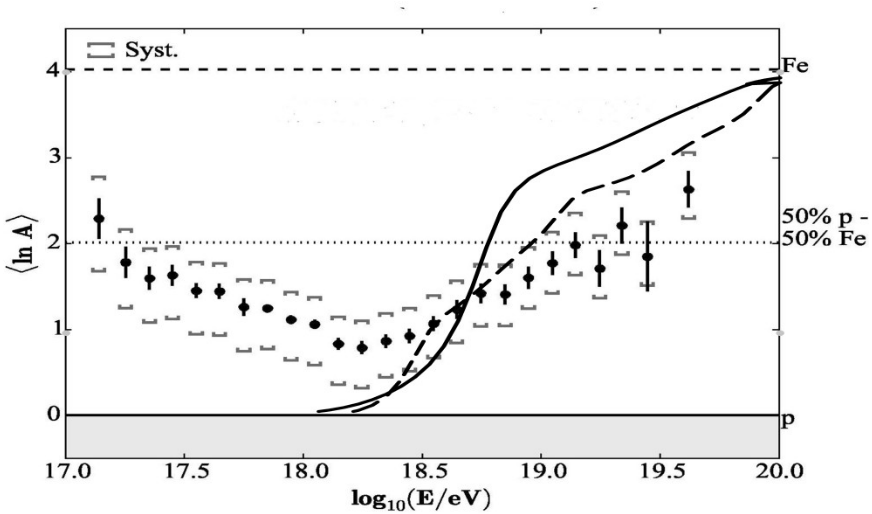


Fig. 5. The average lnA according to the Auger experiment in terms of the model of interactions EPOS-LHC and the results of our calculations.

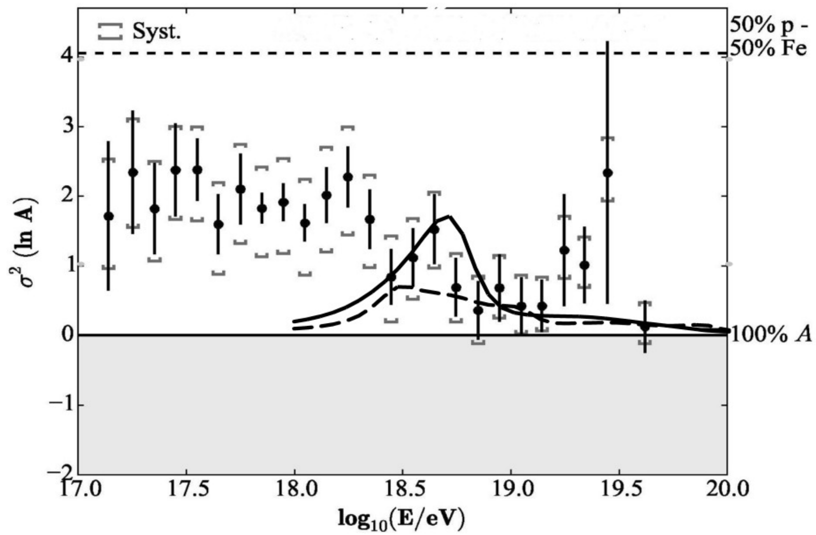


Fig. 6. The dispersion of lnA.

Conclusions

- **It is possible to formulate the inverse problem of determining the spectrum of CR metagalactic sources from the observed spectra.**
- **To explain the observed average lnA needs a very "heavy" chemical composition of the sources. In addition, the spectra of the sources are very hard with the index less than 1, and the cutoff energy $E_{max}=4 \cdot 10^{18}$ Z eV.**