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NUCLEAR PHOTODISINTEGRATION IN THE SOLAR FIELD: NUMERICAL SIMULATIONS OF THE GERASIMOVA-ZATSEPIN EFFECT

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Abstract

Numerical simulations of the photodisintegration process of cosmic nuclei in the photon solar field and of the transport of their charged products in the interplanetary magnetic field have been carried out. The fragmentation probability and the separation between the two fragments have been evaluated as a function of the energy and mass of the primary nucleus, by the use of a realistic model of the interplanetary magnetic field.

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1 INTRODUCTION

The mechanisms which are able to explain the existence of correlations between individual cosmic ray showers at large distances are still not known, representing an interesting challenge in cosmic ray physics. Basically, they may be classified into two different classes: one implying the existence of two primary cosmics, originating from the same source, and producing independent showers in the Earth's atmosphere; the other related to the possibility that a single primary interacts with the interstellar medium and/or the radiation field, thus producing two intermediate products which in turn produce the two showers.

The second category is based on the assumption that the space through which cosmics travel before interacting with the atmosphere is not an empty space; on the contrary it is an extremely complex environment, where different processes may occur. The interstellar medium, representing in our Galaxy about 10% of the stellar mass, includes both gas and dust grains. The interaction of primary cosmics with this medium may result in the production of several classes of particles through inelastic collisions, nuclear excitations and fragmentation processes. Such mechanisms could in principle give rise to correlated showers if the particles produced in the process do not loose their spatial and temporal correlation.

Primary cosmics may also interact with the radiation field present in our Universe. In the close proximity of the Sun, the dominant contribution to this radiation field comes from optical, infrared and microwave photons, whereas the contribution of radiowave, ultraviolet and X photons is negligible. Cosmic nuclei may interact with the field through pair production, hadron photoproduction and photodisintegration processes. This last mechanism, the photodisintegration of heavy nuclei in the solar field, seems to be promising to explain the possibility of large distance correlations between fragments, since the two heavy products could reach the Earth, contrary to what can be expected for electron-positron pairs. The location where the photodisintegration happens should not be too far from the Sun, otherwise the correlation distance between the two fragments would exceed the Earth dimension, thus forbidding their detection. While the photodisintegration cross section of heavy and energetic nuclei is negligible for the infrared and microwave photons, it is relatively high for the optical photons, which are abundant in the solar field. Such mechanism, which was discussed in 1960 by N.M. Gerasimova and G.T. Zatsepin [1] may be responsible for the correlation of individual cosmic showers at large distances, in the order of ten or hundred km. The distance between the showers, the influence of the Sun magnetic field and the probability to observe such events depend however upon several factors, and require detailed numerical simulations, which are the scope of the present work. The present results complement previous analyses reported in recent years [2-5].

2 THE PHOTODISINTEGRATION OF HEAVY NUCLEI IN THE SOLAR FIELD: THE GERASIMOVA-ZATSEPIN EFFECT

The mechanism of photodisintegration of cosmic nuclei in the surrounding of our Sun, due to their interaction with visible photons, and the transport of the charged products - resulting from the disintegration process – through the interplanetary magnetic field, was first investigated by Gerasimova and Zatsepin [1], due to the possible interest such mechanism could have in the measurement of the mass of primary cosmics at very high energies. The possibility to detect the two correlated showers originating in the atmosphere from the fragment nuclei and to measure their energies, could give in principle information on the mass of the primary. The detection of such events would require distances between the two fragments not so high to exceed the realistic size of detector arrays and not too small to avoid possible overlap with single shower events. The original calculations carried out by such authors estimated such distances in the order of a few km; however, such approach neglected the influence of the Sun magnetic field, and only considered the deflection of fragments as due to their transverse momentum. In recent years, additional calculations of such process have been carried out [2,3] with more realistic models of the interplanetary magnetic field, resulting in distances which largely exceed the size of a single shower, extending to ten or even hundred km. The detection of such events would hardly be possible in such case, even with the largest traditional cosmic ray detection arrays.

In the simulations reported here, the problem has been reconsidered, choosing several possibilities for the primary nucleus, from light to intermediate masses, and introducing realistic mass and energy distributions.

The geometry of the photodisintegration process of a complex nucleus in the solar field may be sketched as in Fig. 1. The reference frame is the analog of the galactic frame, with the Earth at the origin and the equatorial plane assumed to be the same as the ecliptic. The photodisintegration process occurs at (l, θ, ϕ), where l is the distance from Earth, θ goes from –π/2 to +π/2 (with the positive sign in the North direction) and ϕ is between –π and +π, positive in the sunset direction. The Sun is along (θ=0, ϕ=0).

To numerically evaluate the photodisintegration probability and the rate of GZ events, a uniform grid in (θ, ϕ) with a step of 2 degrees was assumed, and the free mean path $l(\theta, \phi)$ was evaluated for each direction within this grid. Such quantity depends on the photodisintegration cross section and on the flux of solar photons, according to

$$\frac{1}{\lambda(l)} = \int_0^\infty d\varepsilon \frac{dn}{d\varepsilon}(l)\sigma(\varepsilon')(1+\beta\cos\alpha)$$

where $\sigma(\varepsilon')$ is the cross section, $dn/d\varepsilon$ is the flux, and α is the angle between the incoming direction and the photon direction $\hat{r}$. With this choice, $\cos\alpha = l\,\hat{r}$.

To evaluate the previous integral, the energy limits were chosen between 0 and 10 eV, since the contribution from the flux at higher energies is negligible, as it can be shown from Fig. 2, which reports the quantity dn/dε, for a given value of the distance r (1 A.U.).

The photon flux dn/dε was assumed to be a black body radiation spectrum, with a temperature $T_s = 5770$ K ($K_b\, T_s = 0.5$ eV):

$$\frac{dn}{d\varepsilon} = 7.2\times 10^{7} \frac{\varepsilon^2}{\exp(\varepsilon / K_b T_s) - 1} \left(\frac{1AU}{r}\right)^2 \quad [eV^{-1} cm^{-3}]$$

Concerning the dependence of the cross section upon the energy, if ε′ is the photon energy in the rest frame of the incoming nucleus,

$$\varepsilon' = \varepsilon(\gamma + \sqrt{\gamma^2 - 1}\cos\alpha) \approx 2\gamma\varepsilon\cos^2\left(\frac{\alpha}{2}\right)$$

three regions may be identified: the first one, which extends from 2 MeV up to about 30 MeV (the giant dipole resonance region), and the second region, up to about 150 MeV, can be parameterized according to [3]:

$$\sigma(\varepsilon') = \sigma_{GR}(\varepsilon') \equiv \frac{1.45A(\varepsilon'\ T)^2}{(\varepsilon'^2 - \varepsilon_0^2)^2 + (\varepsilon' T)^2} \text{mb} \quad \varepsilon' < 30 \text{ MeV}$$

$$\sigma(\varepsilon') = \max\left\{\sigma_{GR}(\varepsilon'), \frac{A}{8}\text{mb}\right\} \quad 30 < \varepsilon' < 150 \text{ MeV}$$

The third region, above 150 MeV, which extends above the threshold for pion production, is dominated by the Δ-resonance production, and may be described by

$$\sigma(\varepsilon') = A\left[\frac{1}{8} + S\tilde{\varepsilon}\exp\left(\frac{1-\tilde{\varepsilon}^{\nu}}{\nu}\right)\right]\text{mb} \quad \varepsilon' > 150\text{MeV}$$

where $\tilde{\varepsilon} \equiv (\varepsilon' - 150\text{MeV})/\varepsilon_1$. The values $\varepsilon_1 = 180\text{MeV}$, $S = 0.3$ and $\nu = 1.8$ well reproduce the experimental data. Fig. 3 shows the parameterized cross sections along the overall energy range, for three different cosmic primary nuclei (Fe, O and He).

Once the mean free path of the incoming nucleus in the solar photon field has been evaluated, the relative flux (ratio between the GZ flux and the flux of the unperturbed

$$\eta_{GZ}(\vartheta, \varphi) = \frac{\phi_{GZ}}{\phi_\infty} = 1 - \exp\left(-\int_0^{l_{max}} \frac{dl}{\lambda(l)}\right)$$

primary cosmics) may be determined by:

3 NUMERICAL SIMULATIONS AND RESULTS

3.1 Photodisintegration probability

The numerical integration of the previous equation was carried out up to $l_{\max}$= 80 A.U., since the contributions from larger distances are negligible. Such values of the relative flux are generally very low, especially along directions very far from the Sun. Fig. 4 shows a 3D plot of such quantity as a function of the latitude and longitude angles, in the case of Fe nuclei at an energy of 10^{19} eV. As it can be seen from such plot, the photodisintegration process has a probability which reaches its maximum for directions along the Sun-Earth orientation. The probability depends on the mass of the primary nucleus, as it can be seen from Fig. 5, which reports results for Fe, O and He nuclei of the same energy. The dependence of the relative flux on the latitude and longitude angles is better seen in Figs. 6 and 7, which report results for a Fe nucleus at 10^{19} eV. Additional results may be found in Ref.[4]. Similar trends are observed also for light nuclei (O and He), since the dependence on the orientation is contained in the $dn/d\varepsilon$ factor, which does not depend on the mass of the incoming nucleus. However, the absolute value of the relative GZ flux varies with the mass of primary, reaching values between 10^{-5} and 10^{-4} in case of a Fe primary, and a factor 10 lower for O and He nuclei. This should favor the process in case of Fe nuclei, with respect to the light components in the cosmic ray composition.

Another important factor is of course the primary energy, which influences the cross section dependence, according to the previous formulae. As Fig. 8 shows, the process is enhanced at higher primary energies for a given species.

All the factors contributing to the overall probability however must be taken into account when evaluating the relative GZ flux in realistic cases, since the mass composition and the energy spectrum of the primary both play an important role to determine the final result. As an example (see Fig. 9), at an energy of 10^{17} eV, the contribution to the GZ effect originating from the Oxygen may be higher than that from Iron, due to the cross section dependence.

3.2 Separation between the fragments

An important ingredient to investigate the possibility to detect the fragments produced by the photodisintegration process at realistic relative distances on the Earth is their deflection in the interplanetary magnetic field. To evaluate such deflection, the equation of motion may be integrated from a fixed distance l down to the Earth:

$$\vec{d}_f(l) = \frac{Z_f e}{A_f m\gamma c}\int_{l}^{0} dl'\int_{l'}^{0} dl''\vec{B}(l'')\times\hat{l}$$

where Z_f and A_f are the atomic mass and atomic number of the two fragments and m is the proton mass. The deflection due to the transverse momentum of the fragments is usually negligible, so it was not taken into account in the present calculations.

A realistic model of the Sun magnetic field has been provided by Akasofu et al. [6], who parameterize the field as due to four different contributions [4], the *dynamo* component, the *ring* component, the *sunspot* and the *sun dipole* components. If a cylindrical coordinate system (ϱ, ϕ, z) is used, the different components are shown in Fig. 10 as a function of the distance ϱ. Additional plots of the magnetic field for each geometrical component (ϱ, ϕ, z) are reported in Ref.[4].

Since the two charged fragments are both deflected, previous equation may be used to estimate the relative distance, by replacing Z_f/A_f with $| Z_1/A_1 - Z_2/A_2 |$.

Since the separation distance between the fragments depends on the distance travelled in the magnetic field, the average separation distance may be obtained by a weighted average of the separation distance, taking into account the fragmentation probability:

$$\left\langle d_p(\vartheta,\varphi)\right\rangle = \frac{1}{\eta_{GZ}}\int_{0}^{l_{max}} dl\, d_p(l,\vartheta,\varphi)\frac{d\eta_{GZ}}{dl}$$

where the disintegration probability (right factor in the integral) may be approximated to $1/\lambda(l)$. As an example, Fig. 11 shows the inverse of the mean free path along two selected directions, in the case of a Fe nucleus at an energy of 10^{18} eV. Since the integrand in the previous equation is only slightly decreasing with the distance, the upper limit must be relatively large to ensure convergence, whereas previous authors have used an upper limit of 4-5 A.U. [2,3]. Fig. 12 shows the comparison between the results obtained with an upper limit of 4 A.U. (Left) and with un upper limit of 25 A.U. (Right).

To consider realistic values of the average distance, a rough detector acceptance was taken into account, limiting the integration up to relative distances which can be covered by a large array of detectors, in the order of a few hundred km apart. With such choice, the average distance between the two showers was calculated within an angular grid (θ, ϕ), for several values of the mass and energy of the primary nucleus. Fig. 13 shows the results as contour plots of the average distance as a function of the orientation with respect to our Sun, for a Fe primary nucleus with two different energies. The results nearly scale with the primary energy, due to the factor $1/\gamma \sim A/E$. For a fixed incoming energy however, they scale with the masses approximately as A_1/A_2, so that the contour lines for an Oxygen nucleus will be the nearly same as for a Fe nucleus, with a scaling factor ~16/56.

3.3 Rate of GZ events

The possibility to evaluate the actual rate of GZ events in a realistic situation depends unfortunately upon several factors, which are partly unknown, so very crude estimates are only possible. Such factors include the flux of cosmic primaries and its mass composition, the fragmentation probability, and the fraction of events whose separation is smaller than a selected value, given by the geometrical and acceptance performance of the array under consideration. Concerning the cosmic ray flux and its dependence on the primary energy, a value of the average GZ flux may be estimated as the energy weighted average, with a realistic description of the energy spectrum. Since the fragmentation probability is practically negligible below 10^{16} eV, the average was considered in the energy interval between 10^{16} eV and 10^{19} eV, with a slope parameter equal to 2.7. For a primary Fe nucleus, such average GZ flux is shown in Fig. 14. While experimental factors taking into account the actual coverage of an array and its detection acceptance and efficiency may only be defined for specific detection installations, the problem of the mass composition of high energy cosmic rays is still a matter of debate, and could considerably alter any quantitative estimate of the GZ event rate. Sparse arrays of detectors, with relative distances in the order of ten or hundred km between individual stations should be preferable when looking for such events, in comparison with arrays containing a large number of detectors concentrated in a relatively small area, which are well suited for the reconstruction of individual showers.

4 CONCLUSIONS

The photodisintegration process of cosmic nuclei with masses ranging between He and Fe was considered, carrying out detailed numerical simulations in order to evaluate the fragmentation probability and the separation distances between the emitted fragments.

A realistic model of the interplanetary magnetic field was introduced in the model, which considers all the basic components of the field, in order to transport the charged fragments from the photodisintegration location to the Earth. Results were obtained for different values of the energy of the primary in all the energy range of interest.

Such calculations may be used when looking at the possibility to detect correlated individual showers over large distances by suitable array of detectors. The possibility to estimate the real event rate which could be expected in such situations however needs detailed calculation of the acceptance and detection efficiency, and more realistic information on the mass composition of primary cosmics in the energy range of interest.

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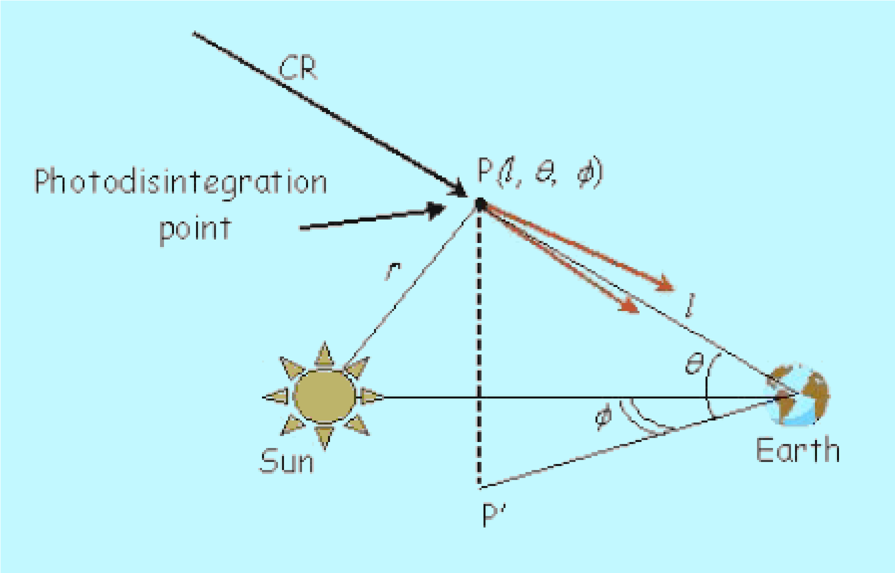

Fig. 1: Sketch of the geometry used for the description of the photodisintegration process of nuclei in the solar field.

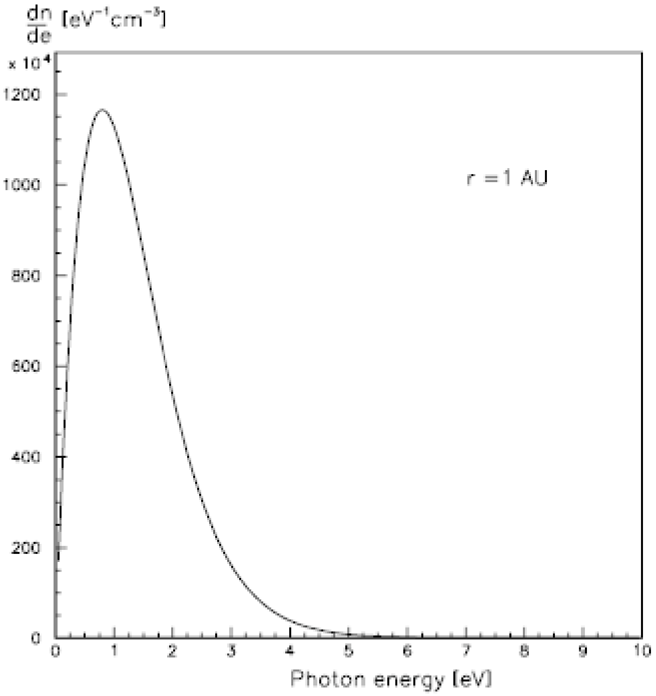

Fig. 2: The solar photon flux as a function of the photon energy, at a distance r= 1 A.U. from the Sun.

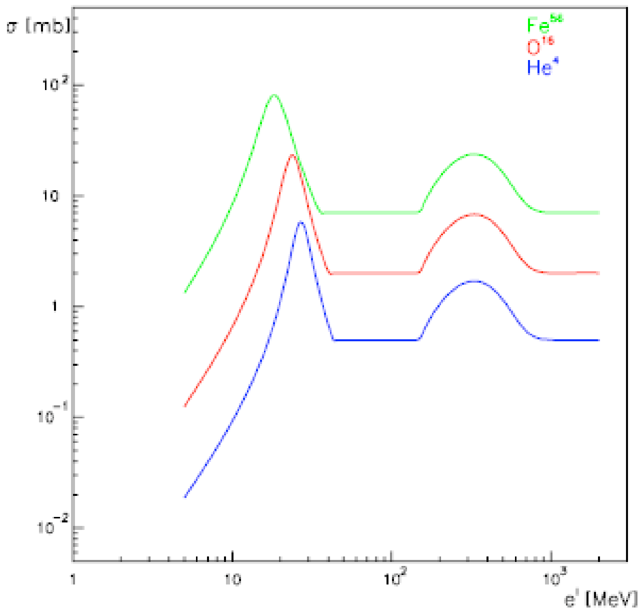

Fig. 3: Photodisintegration cross section, parameterized according to the formulae discussed in the text, for three different primary nuclei.

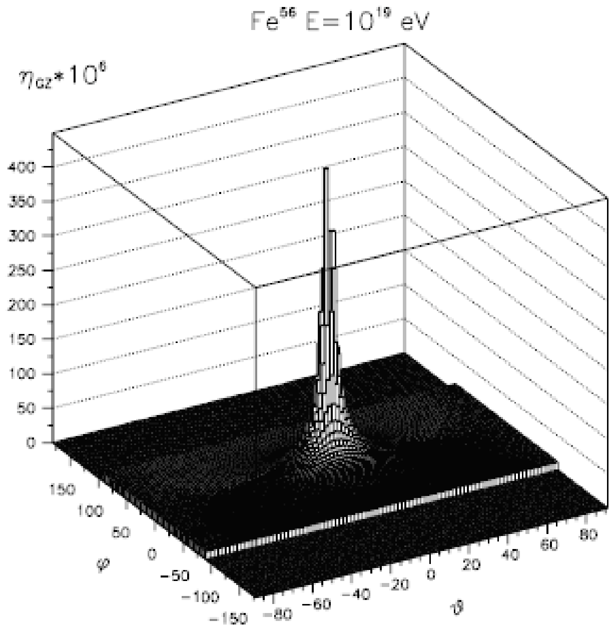

Fig. 4: Relative flux (ratio between the GZ event flux and the unperturbed cosmic flux) as a function of the latitude and longitude angles, for a Fe primary nucleus with an energy of 1019 eV.

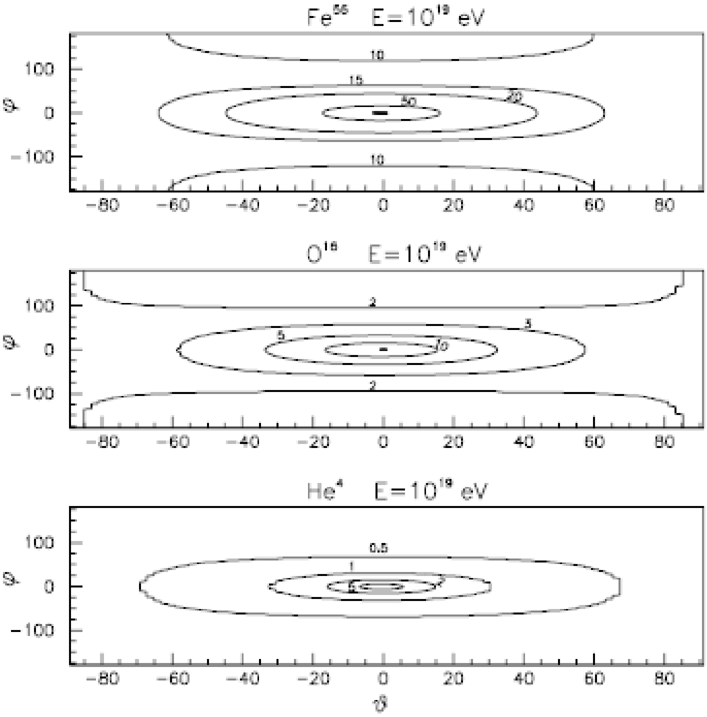

Fig. 5: Contour level plot of the relative GZ flux, evaluated for three different primary nuclei (Fe, O and He) with the same energy. The values are expressed in units of 10-6.

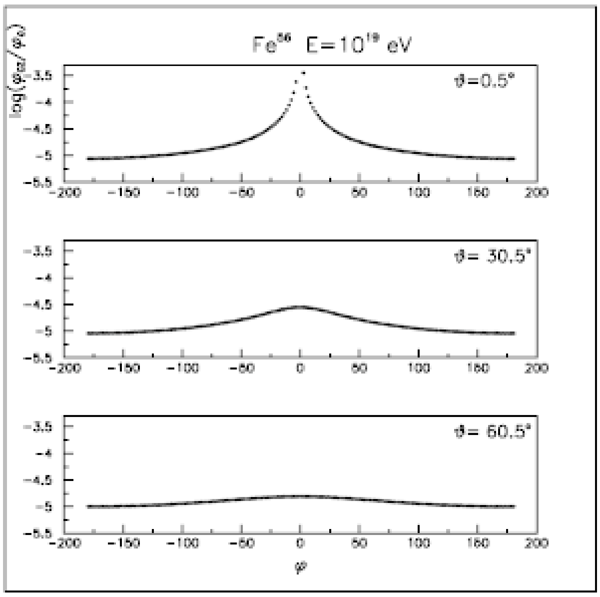

Fig. 6: The relative GZ flux is here plotted as a function of the longitude angle, for three different values of the latitude angle.

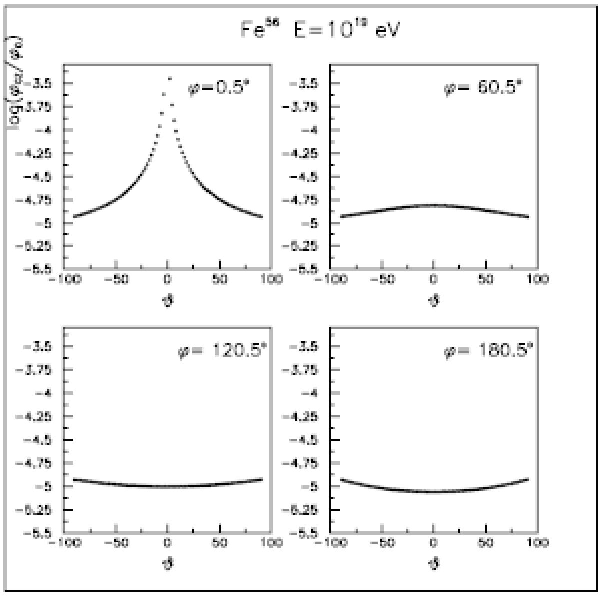

Fig. 7: The relative GZ flux is here plotted as a function of the latitude angle, for different values of the longitude angle.

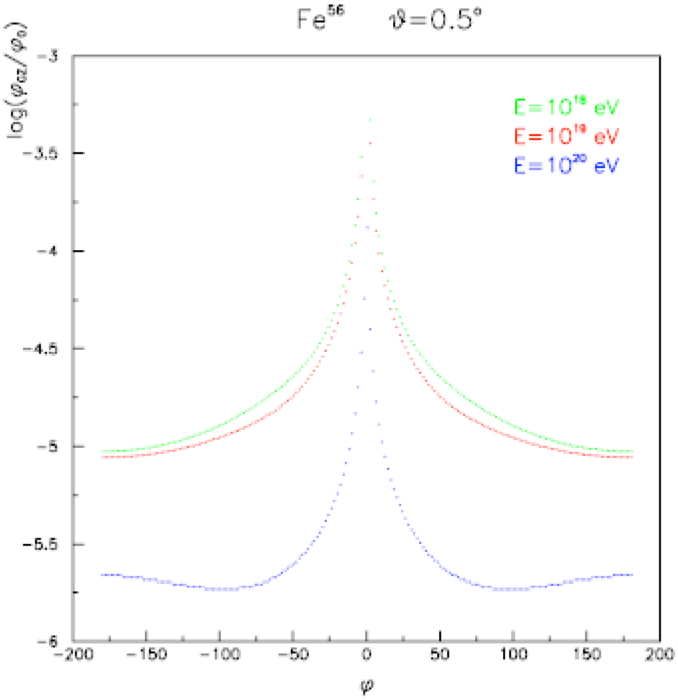

Fig. 8: Comparison between the relative flux at different primary energies.

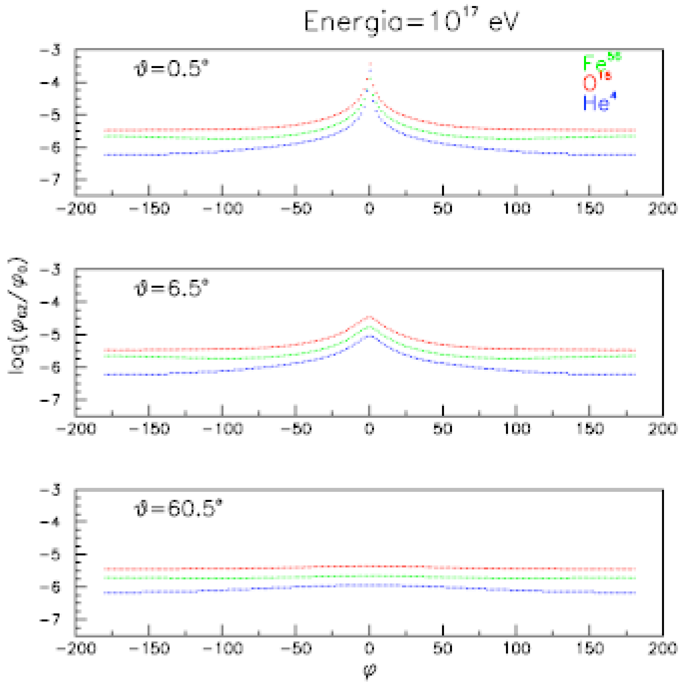

Fig. 9: Comparison between the GZ contributions originating from different primary nuclei, at an energy of 1017 eV.

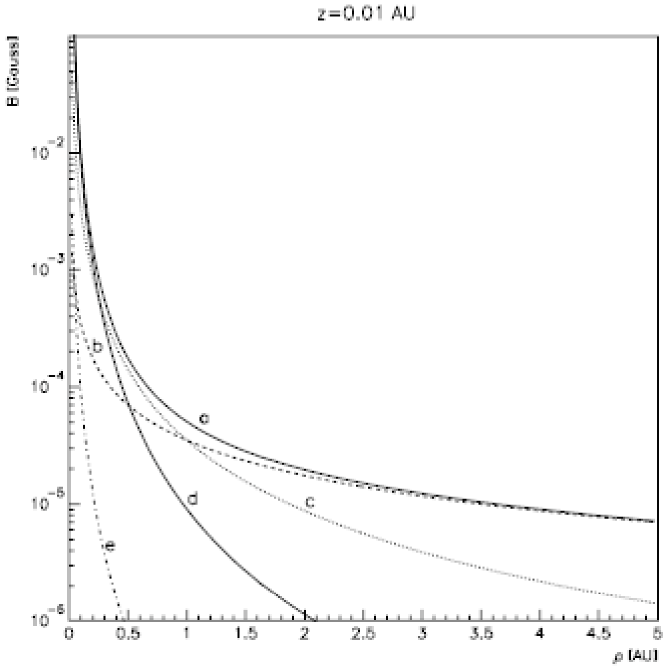

Fig. 10: The different components (b: dynamo, c: ring, d: sunspot, e: sun dipole) and the module (a) of the Sun magnetic field are here plotted as a function of the distance ϱ.

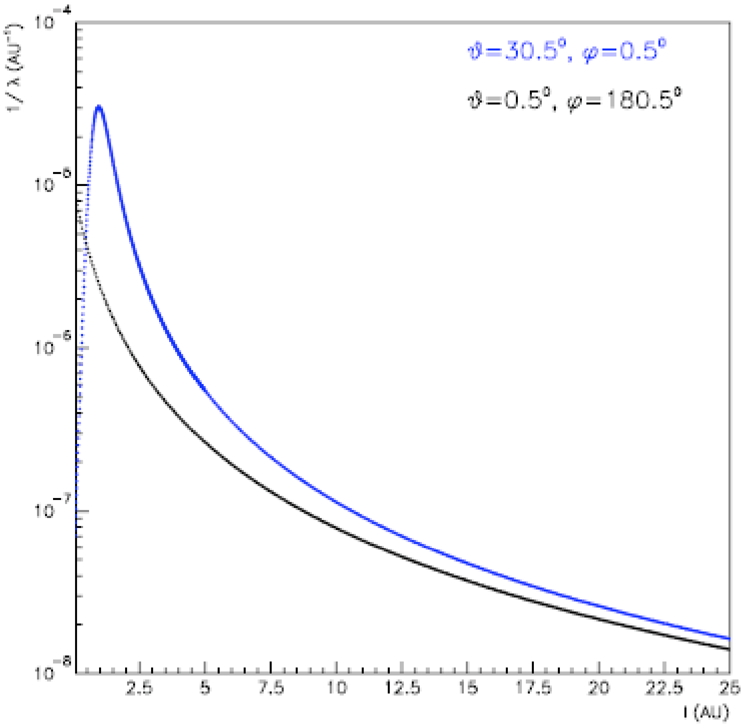

Fig. 11: Inverse mean free path for Fe nucleus at an energy of 1018 eV, as a function of the distance from Earth, for two different orientation of the incoming primary nucleus.

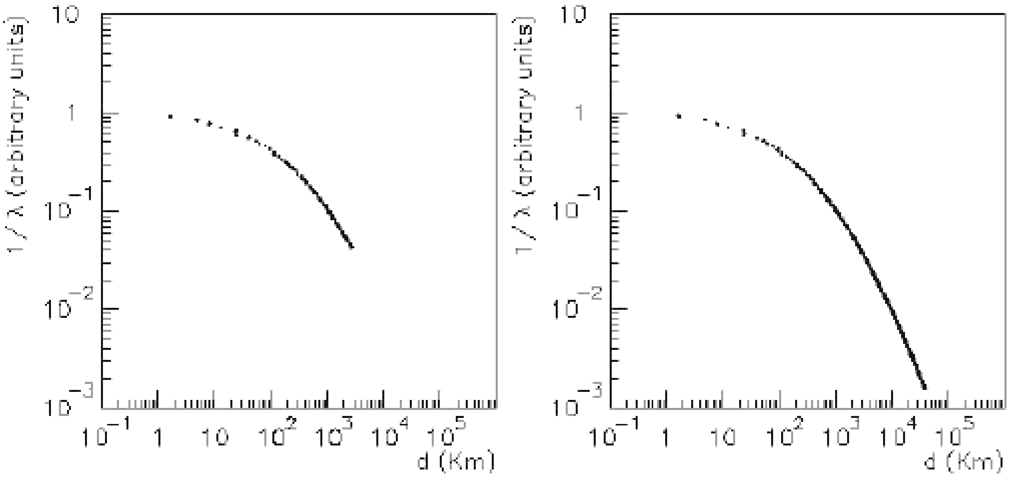

Fig. 12: Distribution of the transverse distance between the two fragments, in case of a Fe primary nucleus at 1018 eV, with upper limits in the integral equal to 4 A.U. (Left) and 25 A.U. (Right).

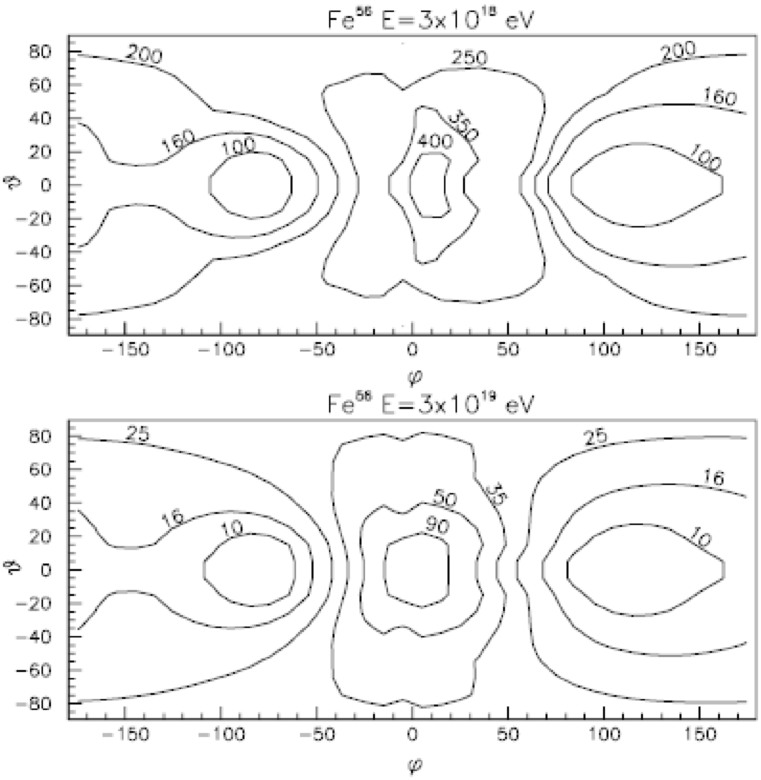

Fig. 13: Contour levels of the average distance between the two fragments, as a function of the orientation with respect to the Sun. Two different values of the primary energy of Fe nuclei were considered. Distances are expressed in km.

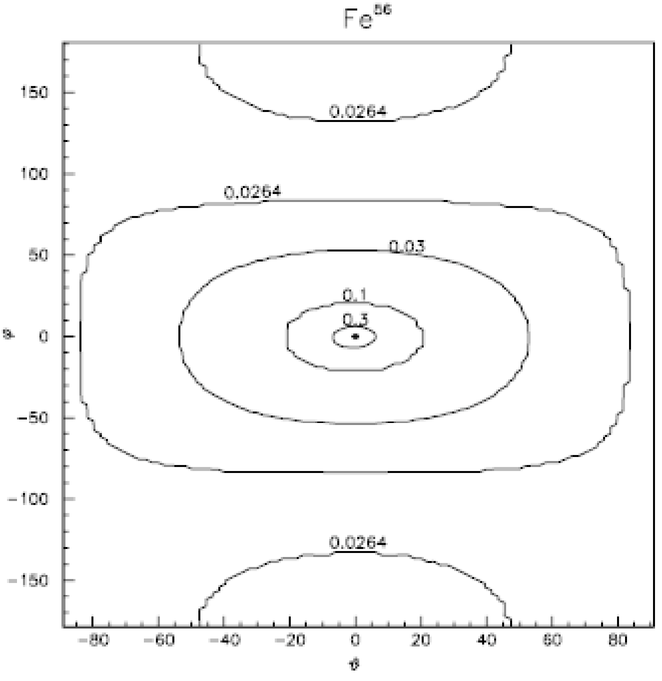

Fig. 14: Contour level plot of the average GZ flux for a Fe primary nucleus, in units of 10-6, from 1016 to 1019 eV.