The Residence Time of Cosmic Rays in the Galactic Disk at Energies around the Knee

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Abstract

The residence time of the galactic cosmic rays in the disk is known from radioactive clocks at energies below 1 GeV and amounts to several million years. It is still unmeasured at very high energy. In this presentation is reported a calculation of the residence time of galactic cosmic rays in the energy range 10^9 -10^{19} eV. The method of calculation uses hundreds millions of cosmic ray trajectories generated in the disk by appropriate algorithms. The magnetic field configuration and gas density which dominate the computed residence time at very high energy are the same adopted for the evaluation of residence time below 1 GeV where a comparison with experimental data is feasible. The computed residence time versus energy has a complex pattern with a maximum value at very low energy, a plateau between 10^{10} and and 10^{14} eV and a smooth decrease at higher energies. A final, second plateau is reached at 10^{18} eV.

1. Introduction

Cosmic rays originate in the galactic disk and propagate through the interstellar medium following the field line pattern of the galactic magnetic field. Regardless of the specific astrophysical sites where acceleration takes place, cosmic rays, as charged particles, describe trajectories in space which are deformed helices. Using physical trajectories of cosmic rays determined by numerical simulation is possible to calculate measurable, physical quantities determined by experiments. Examples of these quantities are the intensity of the cosmic rays, the differential energy spectrum, the asymmetry in the arrival direction, the intensity of the gamma radiation produced by nuclear interactions in the disk in certain energy interval and many others. In this contribution to the conference a calculation of the residence time of cosmic rays in the disk at very high energy is presented. Let us anticipate here that, surprisingly, the same magnetic configuration which causes, above 10^{14} eV, a large overflow of the cosmic rays from the disk is in accord, order of magnitude, with the residence time extracted from radioactive clocks measurements such as Beryllium, Aluminium and Chlorine made at low energy, below 1.5 GeV. In figure 1 is shown the regular magnetic field

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adopted in this calculation.

Cosmic ray trajectories may be classified in three categories depending on the mechanism which breaks and terminates the trajectories.

Following the notation of a previous study of cosmic ray trajectories [1,2] the residence time of cosmic rays τ_D may be expressed by

$\tau_D = f_I \; T_D + f_N \; T_N + f_E \; T_E$

where f_I and f_N, are, respectively, the fractions of cosmic rays terminated in the disk by ionization and nuclear interactions (called nuclear trajectories). The trajectories which penetrate the disk boundaries overflowing into the halo form the fraction f_E and are called halo trajectories. Of course, we have: $f_I + f_N + f_E = 1$. T_I, T_N and T_E are the corresponding residence times of the 3 categories of cosmic rays.

Since at high energies all cosmic rays travel at the speed of the light, c, it follows $L_D =$ c τ_D where L_D is the mean trajectory length of cosmic rays averaged over the entire disk volume. For a uniform distribution of matter in the interstellar medium the grammage is proportional to both τ_D and L_D. Therefore, at high energy the residence time and the mean trajectory length are equivalent physical quantities.

Since the ionization energy losses of cosmic rays in the galactic disk are completely negligible at energies above 5 GeV/u, f_I is zero and then we have: $\tau_D = f_N \; T_N + f_E \; T_E$

The probability for nuclear interaction after the traversal of a gas column of thickness x (g/cm^2) is: f_N= 1 - exp(x/λ_I) where λ_I is the total inelastic nuclear collision length. Finally, since $f_N + f_E = 1$, it results:

$f_E =$ exp(x/λ_I)

indicating that the probability of escape is directly related to the probability of interaction. Otherwise stated, if cosmic rays do not suffer nuclear interactions in the disk they will cross the disk border, populating the galactic halo.

2. Results and conclusion

In figure 2 is shown the computed ratio f_E / f_N as a function of the energy for Helium, Carbon and Iron. This ratio is indicative of the galactic containment of cosmic rays, and more precisely, how the galactic containment changes with energy. There are two plateau for any nuclear species. The first one is at low energy, where the galactic magnetic field has a constant efficiency to retain cosmic rays, approximately between 5 GeV/u and 10 TeV/u. At very high energy, above 3×10^{13} eV, this ratio has a prominent increase reaching the second plateau above 10^{16} eV/u when cosmic ray trajectories cannot be adequately bent by the galactic magnetic field to reverse the initial direction of motion.

In figure 3 is shown the residence time of cosmic rays in the galactic disk

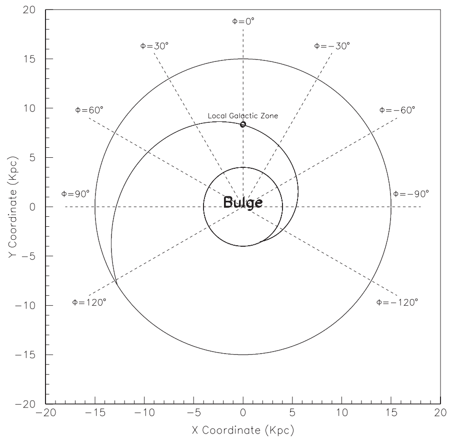

Fig. 1. Field lines projected on the galactic midplane of the spiral magnetic field configuration utilized in the calculation to approximate the magnetic field of the Galaxy. In the Bulge a circular magnetic field is assumed.

as a function of the energy in the interval 10^9 - 10^{18} eV. The residence time is given for two categories of carbon trajectories: nuclear trajectories and halo trajectories. The average residence time may be obtained using the curve f_E / f_N versus energy for Carbon of figure 2. The mean residence times for nuclear trajectories of Helium and Iron are, respectively, 3.2×10^6 and 0.97×10^6 years at the energy of 1 TeV/u.

The magnetic structure of the Galaxy incorporated in the simulation algorithms is the dominant parameter in the study of the residence time. A triple experimental check can be performed against the computed residence time versus energy. At low energy, below 2 GeV/u, using to radioactive clock measurements and above 3×10^{13} eV using the decreasing efficiency (with increasing energy) of the galactic magnetic field in the containment of the cosmic rays. Finally, a third check can take advantage of the characteristic dependence of the asymmetry of the arrival directions of cosmic rays with energy. This asymmetry increases by more than an order of magnitude between 10^{13} and 10^{16} eV where attains a value greater than 1 per cent [3].

3. References

1. Codino A. 1998, Numerical simulation of some fundamental properties of galactic cosmic rays (Vulcano Workshop) page 439.
2. Brunetti M. T. and Codino A. 2000, ApJ 528, 789-798.
3. Hillas A. M. 1984, Ann. Rev. Astron. Astrophys. 22, 425.

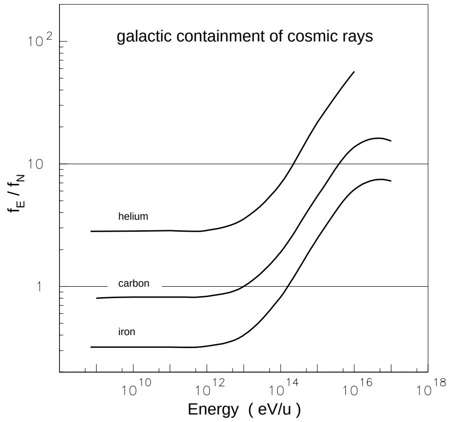

Fig. 2. Galactic containment versus energy evaluated by the ratio between the fraction of cosmic rays escaping from the disk and that interacting inside the disk.

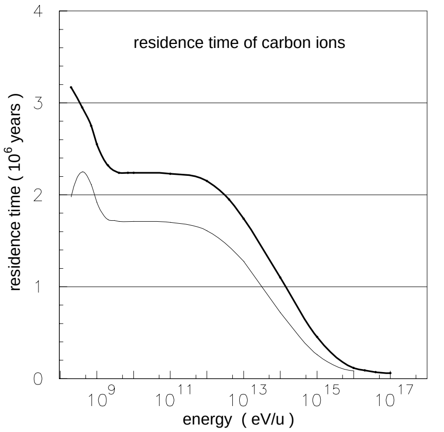

Fig. 3. The residence time of Carbon in the galactic disk versus energy. The thick solid line refers to nuclear trajectories while the thin curve represents the residence time of halo trajectories as explained in the text. The small bump below 1 GeV/u is an effect of carbon trajectories extinguished in the disk by ionization energy losses.