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COMPUTED AGE OF COSMIC RAY PROTONS IN THE LOCAL ZONE OF THE GALACTIC DISK AND ITS DEPENDENCE ON THE MAGNETIC FIELD

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ABSTRACT

The influence of various magnetic field structures of the galactic disk on some fundamental properties of cosmic-ray protons has been investigated with a simulation program which reconstructs cosmic-ray trajectories in the disk volume. Tens of millions of cosmic-ray trajectories have been generated in the galactic disk with 3 different magnetic field configurations (circular, spiral and elliptical). Magnetic clouds with appropriate parameters are introduced to simulate the chaotic component of the magnetic field.

The age, matter thickness and isotropy of cosmic-ray protons feeding the flux in the local galactic volume have been studied as a function of energy, galactic boundaries and some parameters of the magnetic field structures. The age and grammage of cosmic-ray protons in the local galactic region differ by a factor of 2 from those calculated for the whole disk. For the spiral field, the proton age is $7 \cdot 10^6$ years and the corresponding grammage amounts to 11.7 g/cm^2.

1. INTRODUCTION

Computer simulation of cosmic-ray properties presents many advantages in the investigation of cosmic rays and complements the results obtained with analytical methods universally employed in comparisons with experimental data. The simulation results are also useful in evaluating the consequences of theoretical assumptions.

Protons are the most abundant species of charged cosmic radiation. Thus, it is interesting to calculate their age in the galactic disk, since it is representative for all the other cosmic rays. The propagation in the interstellar medium is strongly dependent on the magnetic field structure permeating the galactic volume. The configuration of the magnetic field lines is yet not well known, but it turns out to be a critical parameter when calculating the cosmic-ray trajectories in the disk and, consequently, the age of cosmic rays.

2. THE SIMULATION PROGRAM CORSA

2.1. Galactic features and simulation parameters

Cosmic rays produced and stored in the Milky Way together with the related interactions with the galactic matter and fields form a complex physical system. Simulation algorithms designed to calculate some properties of this system necessarily require a schematization. Interstellar matter distribution, the magnetic field configuration, the cosmic-ray source distribution and the geographical confines of the Milky Way form the basic parameters of this schematization. The bulge is a symmetric ellipsoid with the 2 equal major axes of 8 kpc lying in the galactic middle plane and the minor axis of 6 kpc. Around the bulge a hollow cylinder with a radius of 15 kpc and a constant half height of 250 pc. The regular component of the magnetic field has been parametrized with 3 different shapes: circular, elliptic and spiral magnetic field lines. In the 3 cases the modulus of the field strength is 3 μG. The mean hydrogen density in the galactic disk is taken to be 1 atom/cm^3. Some observational data (Binney and Tremaine, 1987; Blaauw and Schmidt, 1987; Gaisser, 1990) support the oversimplified geometrical patterns utilized in this study. The chaotic component of the magnetic field incorporated in the CORSA code is described elsewhere (Codino, Brunetti and Menichelli, 1995). The source distribution of cosmic rays in the simulation program is that corresponding to the supernova remnants in the Milky Way (Stecker and Jones, 1977 ; Van Den Bergh, 1988).

2.2. Propagation of cosmic-ray protons

Cosmic-ray trajectories are segments of helixes with the helix axis aligned with the regular component of the galactic magnetic field lines. While spiraling about the magnetic field lines, protons suffer ionization energy losses and nuclear interactions in the interstellar medium. Note that primary protons generate secondary protons via elastic and inelastic nuclear collisions. Both primary and secondary protons are included in the results given in this paper. Cosmic-ray protons terminate their lifecycle in 3 modes by: (1) nuclear collisions (nuclear death); (2) ionization energy losses (ionization death); (3) crossing the disk boundaries and overflowing into the halo (disk overflow). The various fractions of proton populations that terminate the lifecycle in these 3 modes as a function of the kinetic energy are given in figure 1 for the circular and spiral magnetic fields. The proton fraction stopped by ionization energy losses levels off at about 0.25 in the kinetic energy interval 5-100 GeV for the 2 field configurations. For primary protons only, this fraction is zero above 0.7 GeV/c.

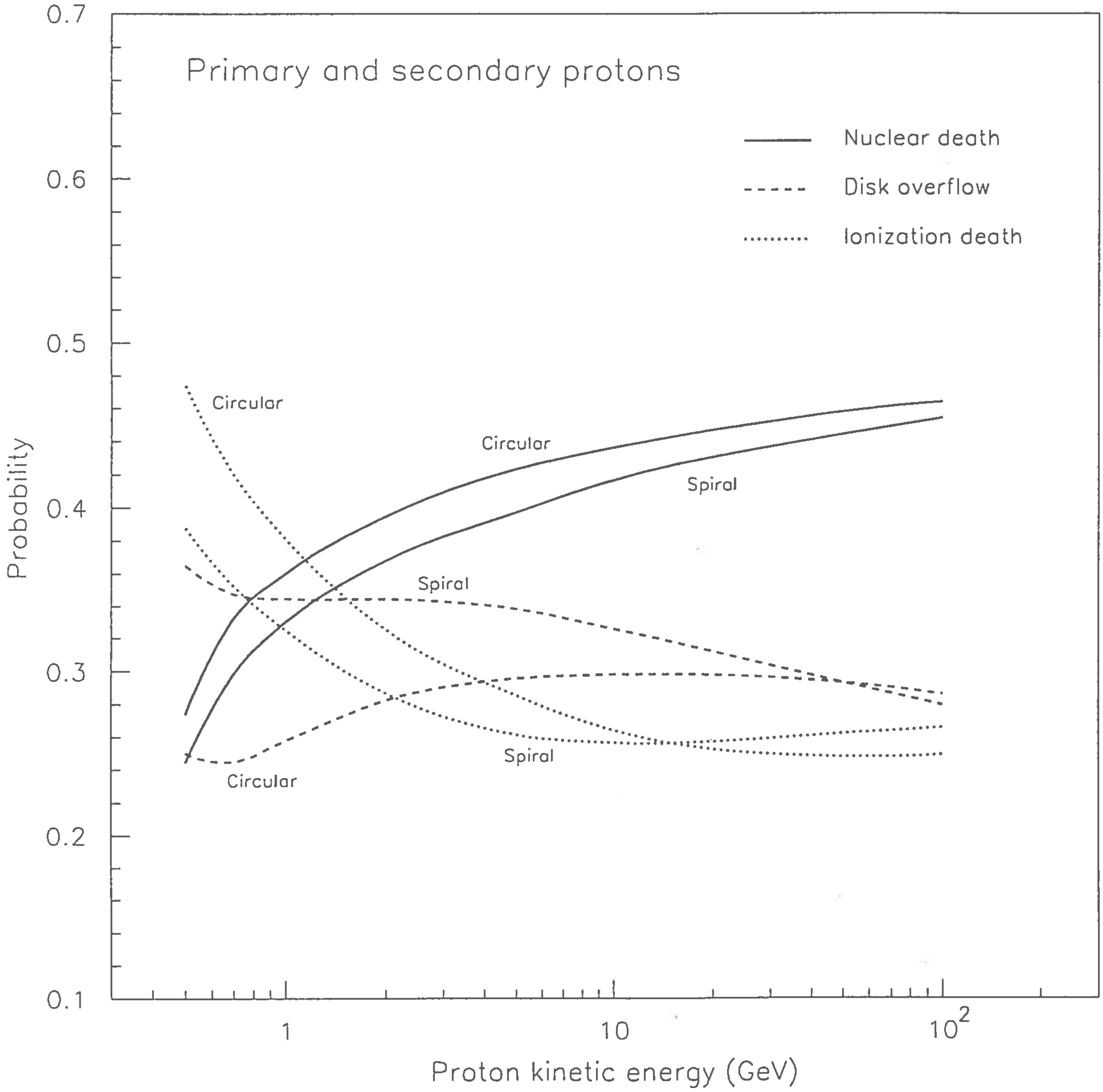

Fig. 1. Fractions of cosmic-ray protons extincted by ionization or nuclear collisions in the galactic disk as a function of the proton kinetic energy for the circular and spiral fields. Primary and secondary protons are included in these calculations. The fraction of protons crossing the disk boundaries is also shown.

Low energy secondary protons provide this larger fraction of cosmic rays extincted by ionization. The fraction of protons undergoing nuclear death has a constant increase from 0.38 to 0.46 in the momentum range 3-100 GeV/c. Similar behaviour is obtained in the elliptical magnetic field configuration.

3. AGE OF COSMIC-RAY PROTONS

The mean residence time of primary and secondary protons of momentum p occupying the disk, $\tau(p)$, has been calculated by the equation:

$$\tau(p) = f_I T_I + f_N T_N + f_E T_E$$

where f_I, f_N and f_E are the fractions of cosmic-ray protons that terminate the lifecycle, respectively, by ionization, nuclear collision or disk leakage and T_I, T_N and T_E, the corresponding partial residence times.

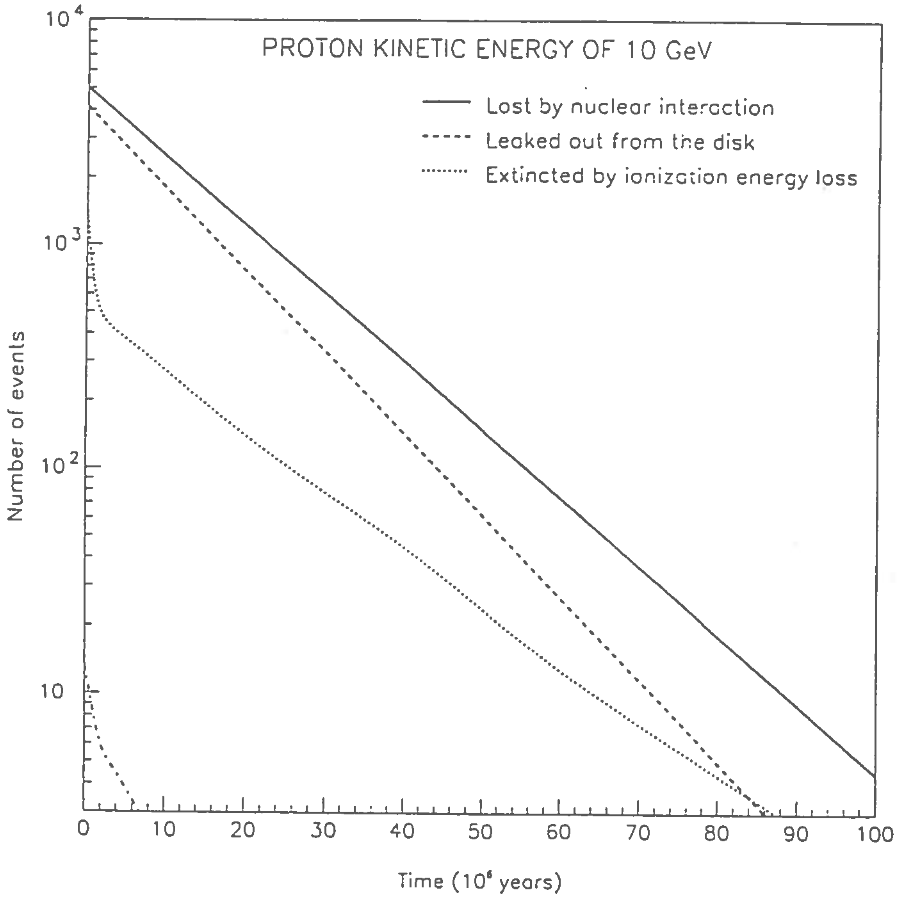

Fig. 2. Residence time spectrum for cosmic-ray protons of 10 GeV for 3 different populations. Protons intercepting the local galactic zone are also shown (dashed-dotted line)

In nuclear collisions of primary protons with interstellar hydrogen, both protons in the final state, if any, are regarded as new cosmic rays and the residence time is calculated accordingly.

The residence time spectrum for the 3 proton populations averaged over the entire disk volume is shown in figure 2.

An ideal observer can measure cosmic-ray properties averaged over the entire disk volume. Instruments, on the contrary, are positioned in the local galactic zone and measure local properties of cosmic-ray protons. The study of both local and global characteristics are of fundamental importance. The mean proton residence time is calculated here in a small volume of the galactic disk and is shown in figure 3.

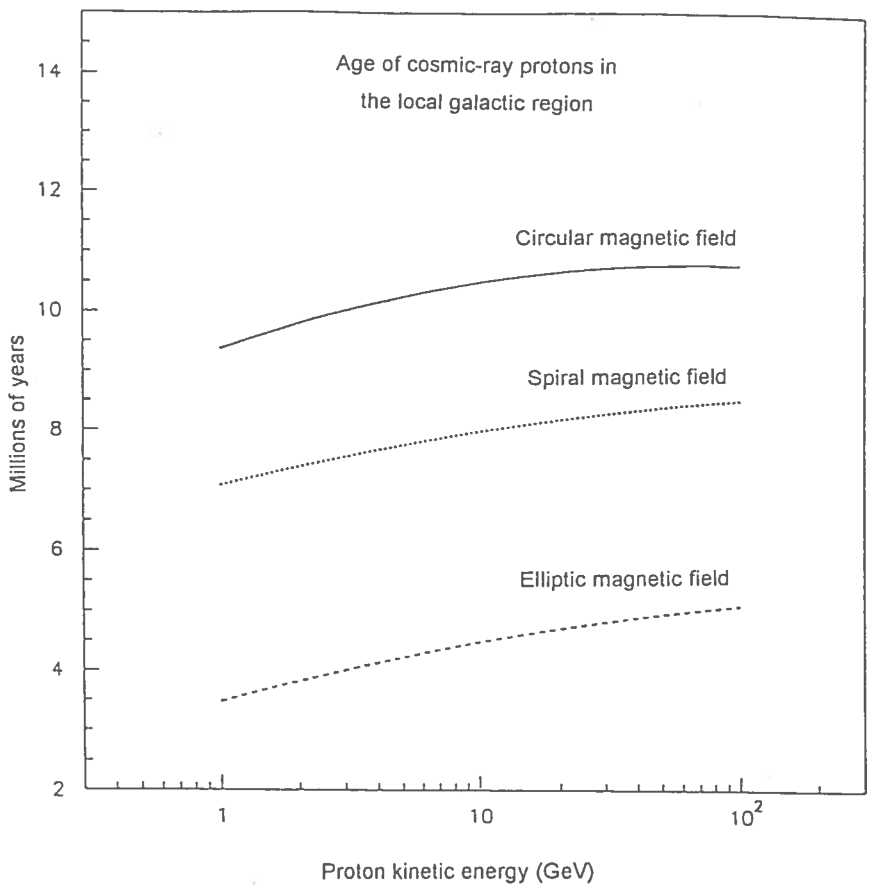

Fig. 3. Mean age of protons intercepting the local galactic region as a function of the primary proton energy for 3 magnetic field configurations.

A sphere of 100 pc in radius is considered as averaging volume when the half thickness of the disk is 300 pc. The center of the sphere coincides with the position of the solar system e.g. 8.5 kpc from the galactic center and 14 pc above the galactic middle plane. The resulting differences in age depend on the magnetic field structures much more than the cosmic-ray energy in the interval 1-100 GeV. The effect of the disk thickness on the mean residence time is shown in figure 4. An almost linear increase of the proton age is observed when the disk thickness varies from 220 to 450 pc. For values of half disk thickness, smaller then 220 pc, the age decreases steeply. The other magnetic field structure have a similar trend.

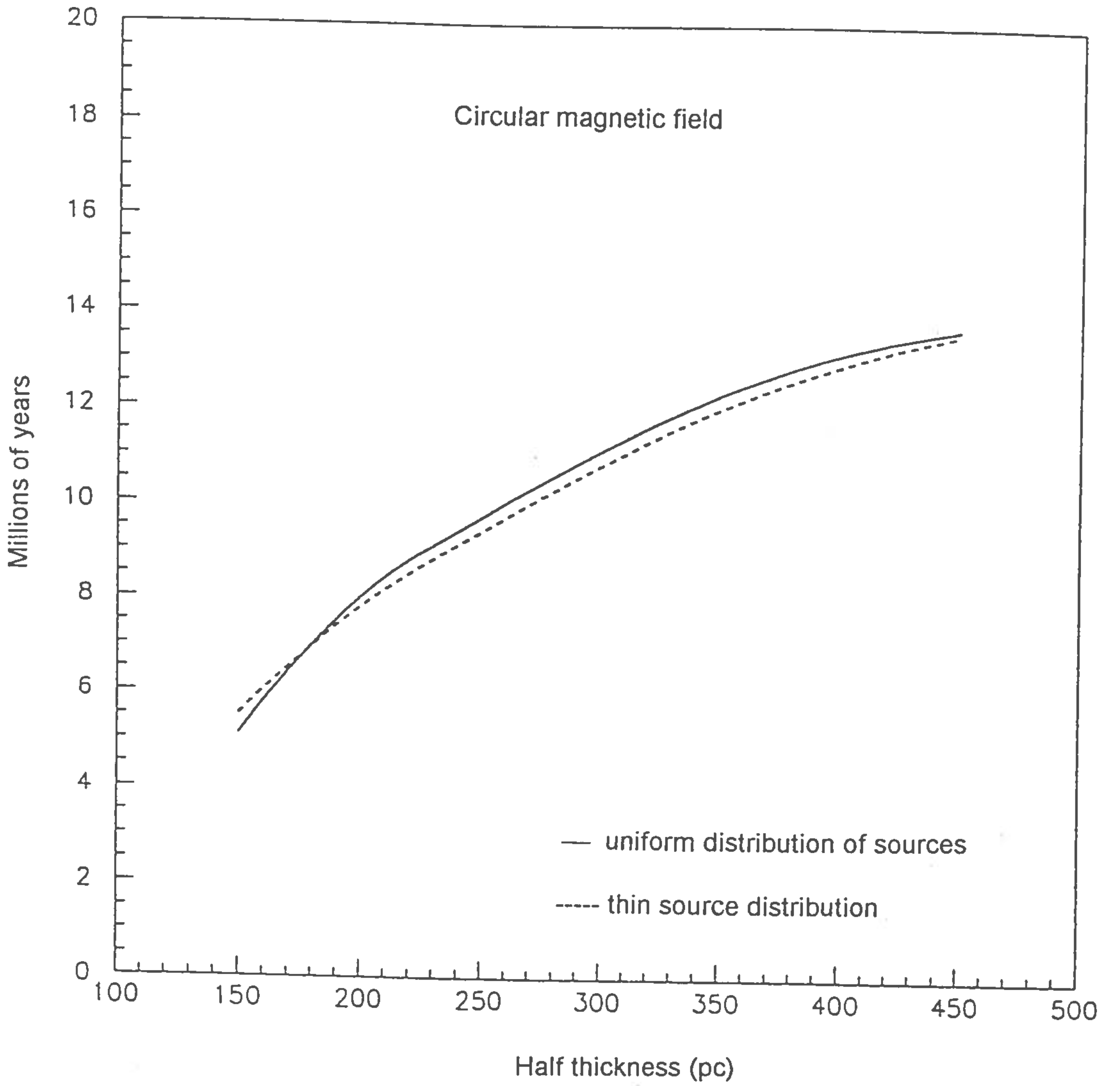

Fig. 4. Proton age in the local galactic zone as a function of the half thickness of the galactic disk from 150 pc to 450 pc for the circular magnetic field configuration.

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