The Residence Time of Cosmic Ray Protons in the Halo of the Milky Way

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Abstract

Radio and optical measurements of the magnetic field structures in the Local Supercluster indicate that spiral galaxies have magnetic haloes extending for tens of kiloparsecs from the galactic planes. The halo of the Milky Way conforms to the typical patterns observed in other spiral galaxies. The residence time of cosmic rays in the galactic halo is primarily determined by the magnetic field shape, the halo dimension and the transport mode. A calculation of the residence time in the halo versus the dimension of the Galaxy, the magnetic field strength, the proton energy and the field configuration is presented. The residence time of cosmic protons of 100 GeV/c traversing a large halo immersed in a circular magnetic field is longer than 10^9 years.

1 Introduction:

Radio continuum emission detected by radiotelescopes in nearby spiral galaxies indicates the existence of regular magnetic fields extending up to 50 kiloparsecs or more from the galactic midplanes. The field strengths even at large distances remain close to 1 μG (Weiner and Williams, 1996). The Galaxy conforms to this typical pattern (Haslam, 1982; Beuermann, 1985). An enormous halo in the Milky Way with a linear extension of 50-100 kpc has important consequences on numerous cosmic-ray properties. Typical halo sizes of 10 kpc above the galactic midplane were considered in diffusion models (Ginzburg et al. 1980; Simpson 1983).

Cosmic rays can traverse the halo volume coming from the intergalactic space or from the galactic disk. The time interval spent in the halo volume is the residence time denoted by T_h. Generally, this quantity for a specified proton rigidity, depends on the position where cosmic rays are injected in the halo and on the observing site. The residence time in the halo is primarily influenced by:

(1) the magnetic field configuration;
(2) the spatial extension of the magnetic field surrounding the disk;
(3) the type of cosmic-ray transport that is most efficient in the halo. In principle, the diffusive, convective and streaming mode of transport have to be considered.

2 Characteristics of the galactic halo:

The geometrical form of the halo is not well defined. The stellar matter of about 150 globular clusters populating the galactic halo with their elongated orbits reach distances of 100 kpc from the galactic center (Harris, 1996). Yet, this stellar volume is not appropriate for cosmic-ray studies. Most properties of cosmic rays are primarily sensitive to the magnetic field structure and particularly to the pattern of the magnetic field lines of the regular component. Thus, the halo of this study is a magnetic halo whose volume is approximated by a symmetric ellipsoid devoid of the galactic disk. The dimension of the ellipsoid is specified by the semimajor axis. The ratio between the two axes of the ellipsoid is taken constant and equal to 3/5. Since observational data do not unambiguously favour a halo dimension, the length of the semimajor axis of the ellipsoid is regarded as a variable parameter in the range 15-100 kpc. The galactic disk is a cylinder of half height of 250 pc and is used only as the internal boundary surface of the halo. Circular magnetic field lines are adopted for the halo. The magnetic field structure utilized in the simulation code is described in detail elsewhere (Codino, 1999). The gas density profile in the halo is steeply decreasing from the disk-halo interface down to the intergalactic space (Dickey and Lockman, 1990). A galactocentric reference frame with cylindrical coordinates r, z and ϕ is used. The solar cavity is positioned at r=8500 pc, z=+14 pc and ϕ=90^0.

The effect of the galactic wind on T_h is ignored in the present calculation.

3 The residence time in the halo:

One fundamental and surprising characteristic emerging from the simulation of proton-proton interactions and trajectories in the galactic disk is the relatively large number of proton secondaries produced at very low energies. These secondaries have not been taken into account in this calculation because they bias the residence time T_h as defined in the introduction.

Primary cosmic protons are injected at the disk boundaries (z=+500 pc, r=8500 pc and ϕ=90^0) and the resulting trajectories determined. The injection coordinate z=+500 pc instead of z=+250 pc (nominal disk boundary) is used to save computing time because it reduces the number of protons penetrating the disk. This choice has a negligible effect on T_h. Only those trajectories that cross the boundary surface of the ellipsoid are considered for the evaluation of the residence time in the halo.

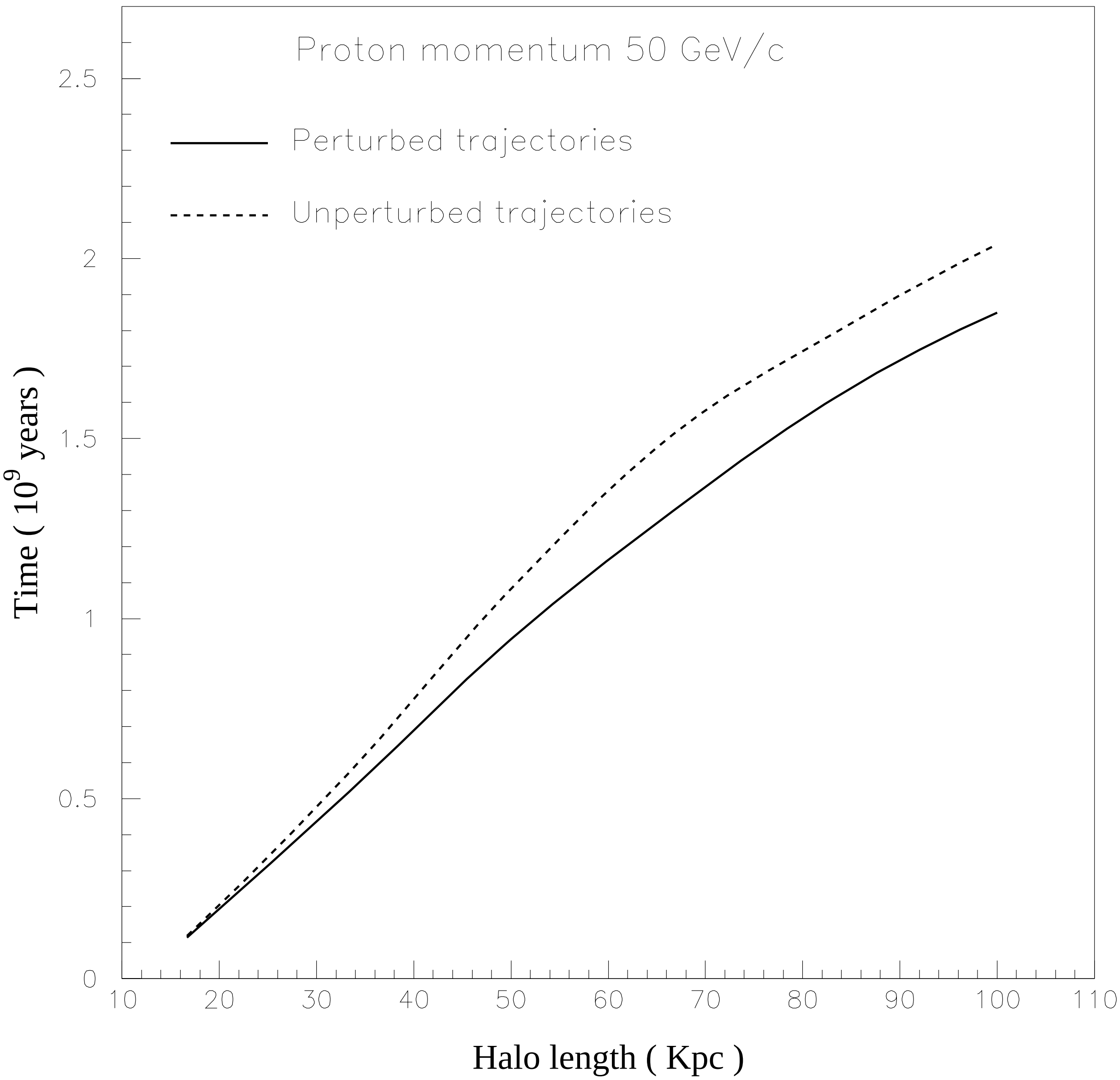

Figure 1: Residence time of cosmic protons in the galactic halo versus the length of the semimajor axis of the halo.

The global effect of the magnetic fields in the halo reduces to a modification of the proton trajectory.

The basic element of a proton trajectory in this computational method is the axis of the helical path of the proton. Let be l_k the length of the helix axis for an arbitrary segment k of the trajectory sampled according to the distribution of magnetic irregularities in the halo. The new helix axis has a spatial shift, ρ_k, in a direction perpendicular to the previous axis, given by $\rho_k = f l_k$ where f is a constant independent on the rigidity and position of the proton in the Galaxy. The constant f is the ratio between longitudinal and transverse propagation of cosmic protons. Since l_k is sampled from the coherence length distribution of the magnetic field in the halo, the constant f may be termed coherence length fraction.

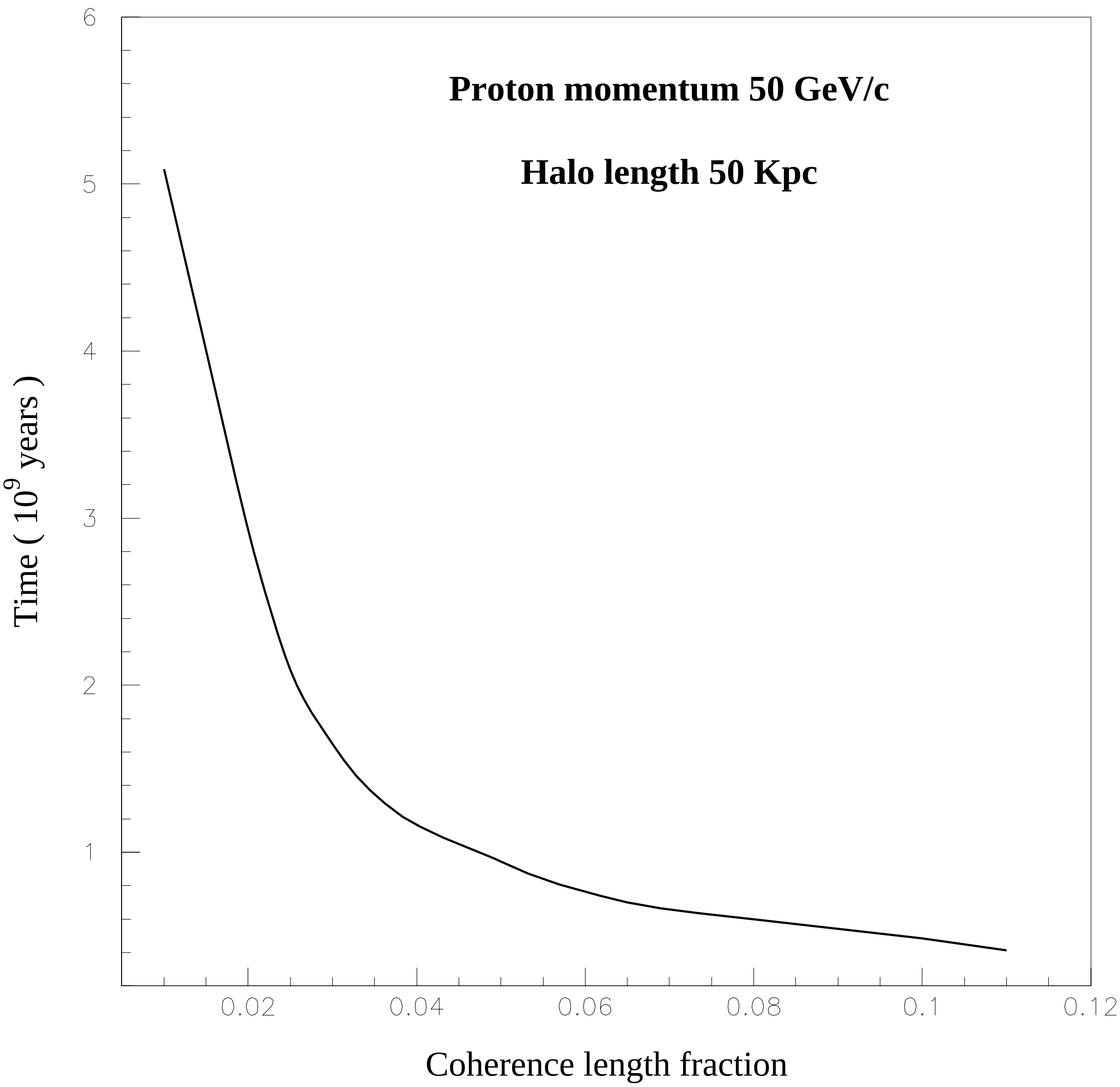

Figure 2: Residence time of cosmic protons in the galactic halo versus the coherence length fraction for a symmetric ellipsoidal halo with a semimajor axis of 50 kpc.

In addition, proton trajectories are fluctuated in the z direction to take into account both the magnetic field component in the z direction and other magnetic substructures. This fluctuation displaces proton trajectories with equal probabilities in the positive and negative z direction by an amount 0.15 z/b where b is the semiminor axis of the ellipsoid. When this effect is included, the trajectories are referred to as perturbed trajectories, when excluded unperturbed trajectories.

The residence time in the halo for protons of 50 GeV/c as a function of the halo dimension is shown in figure 1 with f=0.05. There is only a small difference of 10% between perturbed and unperturbed trajectories. In a halo with a semimajor axis of 60 kpc protons are trapped for 10^9 years. The dependence of the residence time on the coherence length fraction is shown in figure 2 for a halo of 50 kpc. There is a small linear dependence of T_h on f in the interval 0.045$\leq f \leq$0.11 and a strong linear dependence in the interval 0.01$\leq f \leq$0.03. As expected, for small values of f cosmic protons remain trapped in the halo. Analytical calculations show that the diffusion coefficient of strongly magnetized particles transverse to the regular field in inhomogeneities of the magnetic field with a characteristic length significantly larger than the gyroradius of the particles is a fraction 0.1 of the coefficient for the longitudinal diffusion (Jokipii, 1973).

The long residence time of a large halo resulting from this calculation implies that the grammage traversed by protons is not negligible compared to that of the disk. For instance, the grammage of protons of 50 GeV/c in a halo with a semimajor axis of 50 kpc filled with uniform hydrogen density of 10^{-3} atoms per cm^3 is 27 g cm^{-2}. This grammage should be compared with that of 23.1 g cm^2 for the whole disk and with 14.6 g cm^{-2} for an observer in the local galactic zone (Brunetti and Codino, 1998). Note that this last calculation includes both primary and secondary protons in the evaluation of the grammage, a circumstance that tends to reduce the computed grammage.

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