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Age of cosmic beryllium and grammage inferred by the unstable-to-stable beryllium isotopic ratio

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Abstract. A few millions of ^9Be and ^{10}Be trajectories originated in the galactic disk are generated by a simulation code using a simple configuration of the galactic magnetic field. The grammage and age of beryllium are studied as a function of the position of the beryllium sources in the disk. The $^{10}Be/^9Be$ ratio versus energy is calculated and compared with the experimental data.

1 Introduction

The simulation of cosmic-ray trajectories in the galactic magnetic field allows a simple, direct, even visual analysis of many features and basic properties of galactic cosmic rays. Cosmic-ray trajectories are segments of deformed helixes connecting the sources placed in the interstellar medium to the observing sites which are placed in the solar cavity. This paper deals with the propagation of cosmic Beryllium in the galactic disk using the method of trajectories.This calculation reports a relationship between age, grammage and $^{10}Be/^9Be$ ratio versus beryllium energy and also illustrates how complex is the interpretation of $^{10}Be/^9Be$ ratio determined by measurement. The approximations used in the simulation algorithms that determine the trajectories of the cosmic rays are given elsewhere (Codino et al. 1995, Brunetti and Codino 1997).

The dominant factor affecting the age and grammage of cosmic Beryllium is the shape of the galactic magnetic field. The influence of the galactic magnetic field on grammage and age of cosmic rays has been already investigated in the energy range 0.1-100 GeV using circular, spiral and elliptical field structures with a chaotic component (Codino 1998 ; Brunetti Codino 2000).

Many experiments have measured the $^{10}Be/^9Be$ ratio or the surviving fraction of ^{10}Be (see for example, Connell 1997, Lukasiak 1997, Webber and Soutoul 1998). Presently, a balloon-borne experiment (Isomax) aims to accurately measure the $^{10}Be/^9Be$ ratio up to an energy of 1.7 GeV/u (Mitchell et al., 1999).

This calculation complements the results on age and grammage of Beryllium reported in two previous papers (Brunetti Codino 1997; Codino and Vocca 1999).

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2 Results of calculation

A brief description of the parameters of this calculation follows. The magnetic field in the disc is decomposed in a regular component and a chaotic component. The field strength of the regular component is 3.0 μG. The pattern of the magnetic field lines is based on observational data, which favor spiral field structures. Accordingly, a spiral field is adopted. Cylindrical, galactocentric coordinates r, ϕ and z are used where z is the elevation from the galactic midplane, r is the distance from the symmetry axis and ϕ is the azimuthal angle as shown in Fig. 1. The Bulge is a symmetric ellipsoid with the major semiaxis lying in the galactic midplane, 4 kpc long and a minor semiaxis of 3 kpc. The disk has a radius of 15 kpc and a constant thickness of 250 pc. The local galactic zone is a sphere with a radius of 100 pc concentric with the solar cavity. This sphere is positioned at the coordinates z = 14 pc, r = 8500 pc and ϕ = 90 degrees (see Fig. 1). The interstellar gas density is taken as pure hydrogen uniformly distributed in the galactic disk. The mean hydrogen density is 1 atom cm^{-3} (Gaisser 1990). The simulation code determines the probability that a cosmic Beryllium intercepts the local zone for any initial position in the disc volume. The stable isotope ^9Be and the unstable ^{10}Be with a half-life of 1.6×10^6 years are used in this calculation. If a uniform distribution of beryllium sources filling the entire disc volume of 529 kpc^3 is used, the probability for a cosmic Beryllium of entering the local zone is about 10^{-5}, and accordingly, the computing time for an adequate number of trajectories becomes exceedingly long. In order to increase the number of trajectories in the local zone, the beryllium sources are positioned along the magnetic field line which encounters the center of the local zone as shown in Fig. 1. This magnetic field line is called principal field line. Note that if the beryllium sources are positioned well aside from the principal field line, the probability of arriving at the local zone becomes negligible.

In Fig. 2 is given the grammage traversed in the interstellar medium by ^9Be and ^{10}Be for three different positions of the sources as a function of the kinetic energy. The distances of the sources from the local sphere are -4.3, -2.2 and -0.8 kpc which correspond to ϕ angles of -30, -15 and -5 degrees, respectively (see Fig. 1). In Fig. 3 is reported the time taken by the ^9Be (solid line) and ^{10}Be (dashed line) to reach the local galactic zone from the 3 distances of -4.3, -2.2 and -0.8 kpc along the principal field line.

Fig. 4 reports the $^{10}Be/^9Be$ fraction versus energy in the same conditions of Figs. 2 and 3. Note that the energy in Fig. 4 is the initial energy of Beryllium at the source, and not that of the Beryllium arriving at the local galactic zone.There is a slight shift between the two energies in the low energy interval, close to 0.2 GeV/u. For simplicity, the curves in Fig. 4 assume an equal production of ^9Be and ^{10}Be at the sources. Accordingly, a comparison with the experimental data needs to take into account the production cross sections of ^9Be and ^{10}Be via Carbon, Oxygen, Nitrogen and other heavier nuclides interacting with protons in the interstellar medium. The surviving fraction of ^{10}Be may be also used for a comparison with observations. At the energy of 0.3 GeV/u the surviving fraction of ^{10}Be calculated here is 0.667 for the source positioned at ϕ= +15 degrees. The surviving fraction of ^{10}Be becomes 0.776 at 0.9 GeV/u and 0.946 at 10 GeV/u, for the same source.

3 Discussion and Conclusion

The method of trajectories allows us to directly determine important features of cosmic rays. Some of these features are quite different from the results of leaky box models or diffusion models. For example, previous calculations obtained using the method of trajectories indicate that:

1. An observer positioned in the local galactic zone (any instrument is necessarely placed in the local galactic zone) measures a grammage approximately double than that traversed by cosmic rays propagating through the entire disc volume. This effect, explained elsewhere (Brunetti and Codino 2000) is due to the annular shape of the galactic magnetic field and the finite size of the disc.

2. The computed grammage traversed by cosmic rays beyond a few GeV/u depends on the atomic weight of the cosmic rays and is different for different nuclides. For example, protons of 5 GeV uniformly generated in the disc traverse a grammage of 14 g cm^{-2} while ^9Be of 5 GeV/u, also uniformly generated, traverse only 5.4 g cm^{-2}. This results from a combination of parameters such as the regular magnetic field, the nuclear cross sections of cosmic rays with the interstellar medium, the limited thickness of the disc and the position of the sources.

The results discussed above indicate that the interpretation of the measurements of the $^{10}Be/^9Be$ ratio requires a detailed mapping of the source distribution in the disc volume and the effective pattern of the magnetic field lines in the Galaxy.

The grammage and age reported in Figs. 2 and 3 are straightforwardly related to the $^{10}Be/^9Be$ ratio shown in Fig. 4. This calculation has been only made for 3 particular positions of the beryllium sources in the energy range from 0.2 to 100 GeV/u but may be repeated for any desired set of source positions.

The relationship between age, grammage and $^{10}Be/^9Be$ ratio shows the flexibility and usefulness of the method of trajectory. Thus, a source positioned along the principal field line at a distance of -4.3 kpc from the local zone, emanating ^9Be and ^{10}Be of 2 GeV/u with equal abundance, would yield a $^{10}Be/^9Be$ ratio of 0.74. A closer source placed at -0.8 kpc from the solar cavity would yield a ratio of 0.94.

It is clear that a comparison of this calculation with measurements of $^{10}Be/^9Be$ ratio requires a precise spatial distribution of beryllium sources in the disc. For a uniform distribution of beryllium sources the age and grammage of Beryllium has been calculated in a previous paper (Codino and Vocca 1999). From the results shown in figures 2,3 and 4 it is evident that a source distribution in the vicinity of the solar cavity, within a few kiloparsecs along the principal field line and around it , dominates the $^{10}Be/^9Be$ ratio.

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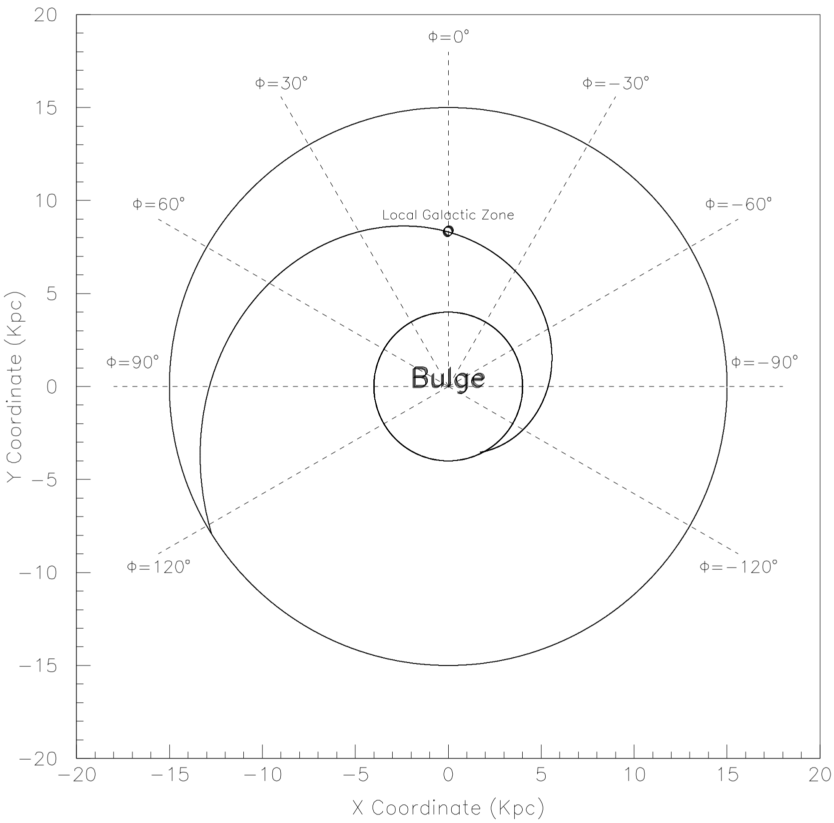

Fig. 1. Projection of the disk onto the galactic midplane. The disk radius is 15 kpc and that of the Bulge 4 kpc. A field line of the spiral magnetic field rooted in the Bulge and terminating at 15 kpc (solid line) is called principal field line.This line intercepts the center of the local galactic zone.Note that the distance from the local zone along the principal field line is taken negative for negative ϕ angles

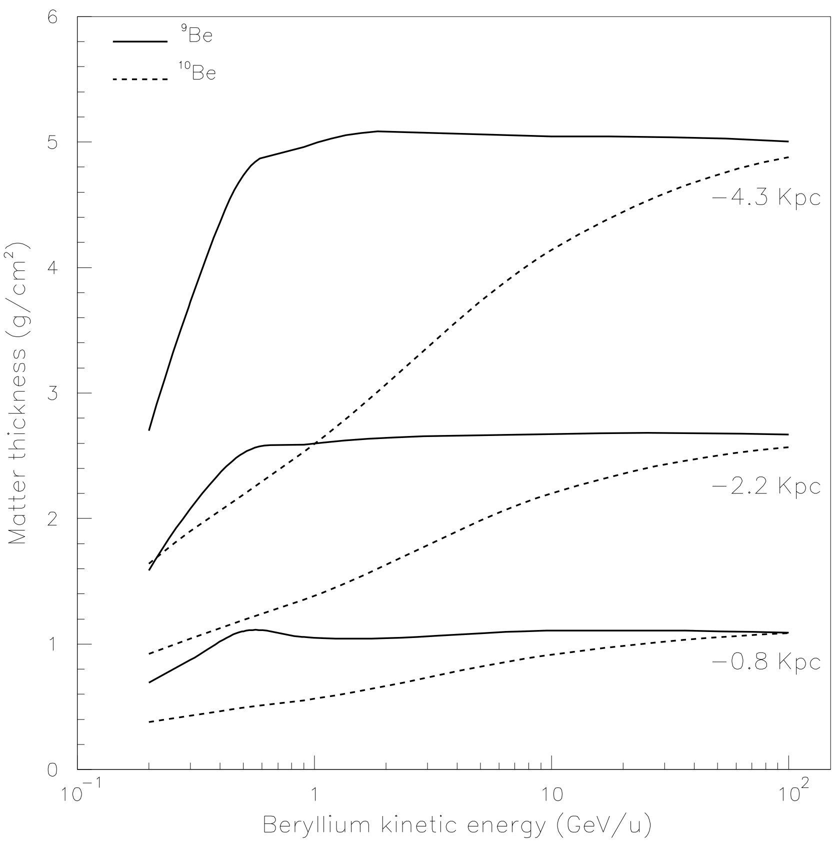

Fig. 2. Grammage swept out by ^9Be and ^{10}Be versus kinetic energy. The beryllium sources are positioned along the principal field line at a distance of -4.3, -2.2 and -0.8 kpc from the local zone.

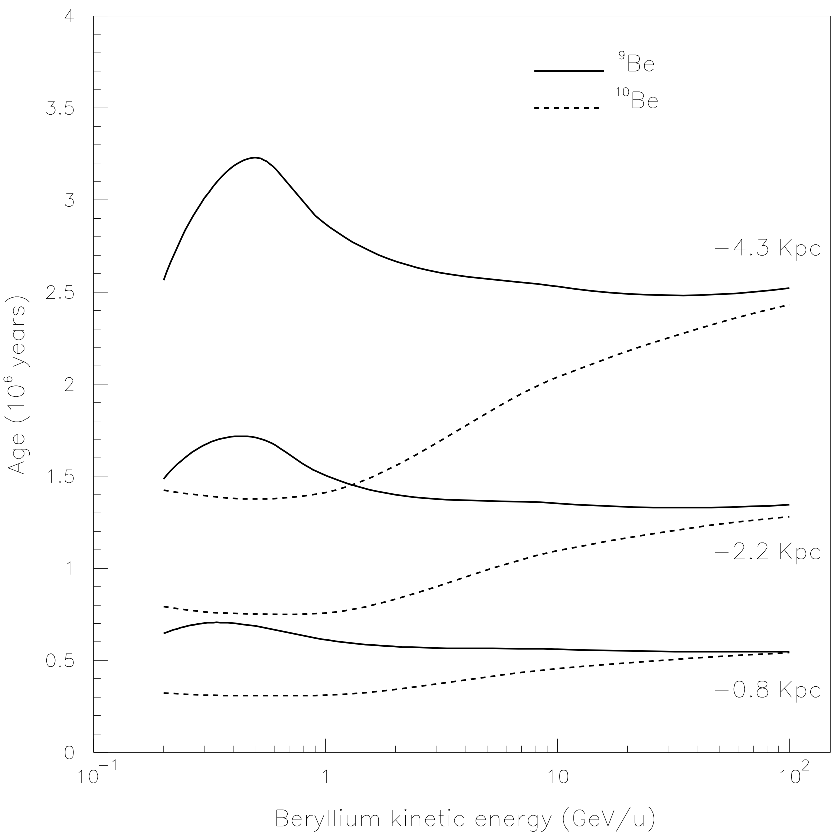

Fig. 3. Age of ^9Be and ^{10}Be versus kinetic energy. The beryllium sources are positioned along the principal field line at the distance of $-4.3, -2.2$ and -0.8 kpc from the local zone.The bump in the age curve of ^9Be (solid curve) is due to the relativistic, gentle rise of velocity with the kinetic energy.

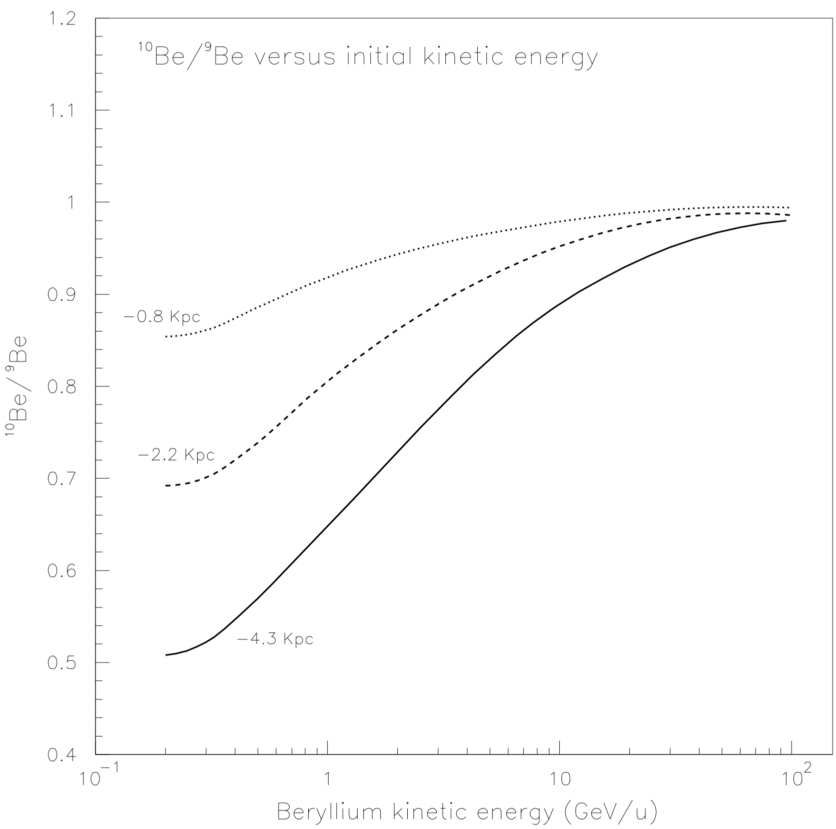

Fig. 4. The ratio $^{10}Be/^9Be$ versus energy. The beryllium sources are positioned along the principal field line at the distance of $-4.3, -2.2$ and -0.8 kpc from the local zone. Note that in this calculation the production of ^9Be and ^{10}Be by spallation of heavier nuclei in the interstellar medium is taken with equal abundance.