Implications for Cosmic Ray Propagation from ACE Measurements of Radioactive Clock Isotope Abundances

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Abstract

Galactic cosmic rays (GCR) interact to produce secondary fragments as they pass through the interstellar medium (ISM). Abundances of the long-lived radioactive secondaries ^{10}Be, ^{26}Al, ^{36}Cl, and ^{54}Mn can be used to a derive the confinement time of cosmic rays in the galaxy. Abundances for these species have been measured recently using the Cosmic Ray Isotope Spectrometer (CRIS) aboard the Advanced Composition Explorer (ACE) spacecraft. To interpret this data we have modeled the production and propagation of the radioactive secondaries, taking into account recently published isotopic production cross-sections. Abundances for all species are consistent with a confinement time of $\tau_{esc} \sim 22\times10^6$ years.

1 Introduction:

Information about the spallation of galactic cosmic rays into secondary fragments as they propagate through the ISM is retained in the abundances of those fragments observed at Earth. Stable secondaries act as a gauge for the amount of ISM material the GCRs traverse but offer few if any details about the material distribution or propagation history. Abundances of the long-lived secondary radionuclide "clocks" reflect a balance between production by spallation in the ISM and decay or escape during the propagation time of cosmic rays, and thus probe these details mentioned above. The abundance of the clock isotope^{10}Be has been measured for about 20 years, but recent measurements of other species with a variety of halflives such as ^{26}Al and ^{36}Cl using Voyager, Ulysses, and CRIS can present a more comprehensive picture of GCR propagation.

The decay of these clock isotopes provides the necessary timing to study propagation history, but specific interpretation of the clock abundances depends on the type of propagation model used. The so-called "leaky box" model (LBM) assumes a homogeneous distribution of ISM matter and predicts a galactic confinement time and an average ISM density from clock isotope abundances. Under certain circumstances, the leaky box model is a suitable approximation to more realistic models of GCR diffusion, but observable differences arise in the shorter halflife clock abundances if one assumes significant inhomogeneities in the local matter distribution. Despite the oversimplified nature of the LBM, abundance predictions for a variety of GCR species have been fairly consistent with measurements. The galactic geometry for diffusion models is not well-constrained by observation, and in general the interpretation of clock abundances is limited to a particular choice of geometry. One recent diffusion model uses the fractional abundance of the clock isotopes which survive propagation to predict a local galactic diffusion coefficient for various geometries (Ptuskin and Soutoul 1998), which offers a straightforward experimental test.

2 Propagation Model:

A steady-state LBM was used to calculate the post-propagation GCR abundances observed by CRIS (Binns et al. 1999). With the exception of an overabundance of ^{22}Ne, the source abundances were taken to be solar, adjusted for a FIP-like fractionation. The source spectra obey a power-law dependence in rigidity. Ionization energy loss, spallation, radioactive decay, and single electron attachment and stripping rates in the ISM were incorporated in the model. The composition of the ISM was chosen to be 90% H, 10% He. The amount of energy loss was adjusted to reflect a 25% ionized H population in the ISM, consistent with observations (Nordgren et al. 1992).

The GCR pathlength distribution (PLD) for a single leaky box is exponential. The mean ISM pathlength was adjusted to match four secondary to primary ratios from CRIS (B/C, F/Ne, P/S, and (Sc+V)/Fe). HEAO-3 data at the higher energies were used as a consistency check (Englemann et al. 1990). As suggested by previous work (e.g., Lukasiak et al. 1994), we assume the following form of the mean pathlength λ:

$$\lambda = \lambda_o \beta^n (\frac{R}{R_o})^{-\gamma}, \text{ for } R > R_o \quad \lambda = \lambda_o \beta^n, \text{ for } R < R_o \quad \text{where } R\text{=rigidity, } \beta = v/c,\ R_o \sim 2 \text{ GV} \qquad (1)$$

Fitting the energy dependence of the secondary to primary ratios is crucial for determining the ISM density and confinement time over the energy range of the data. Typically, a value of n=1 has been used in many models. Tan et al. (1987) suggest that suppression of GCR diffusion can lead to higher values of n. Previous low energy experiments which have measured these ratios at multiple energies indicate a need for n $\sim$2-4 to fit the data (e.g., Krombel and Wiedenbeck 1988), and this trend is present in the CRIS data as well.

Our model requires slightly different mean pathlengths to fit CRIS low-Z ratios and the sub-Fe/Fe ratio. PLDs which are truncated at shorter pathlengths have been suggested before as a resolution to this discrepancy (e.g., Garcia-Munoz et al. 1987, Webber 1993), consistent with models including concentrations of matter around discrete GCR sources in the galaxy. For this study, we adjusted the mean pathlength for each clock isotope to match the secondary to primary ratio data for the parent nucleus which contributes the most to that clock species. Consequences of this method are addressed later.

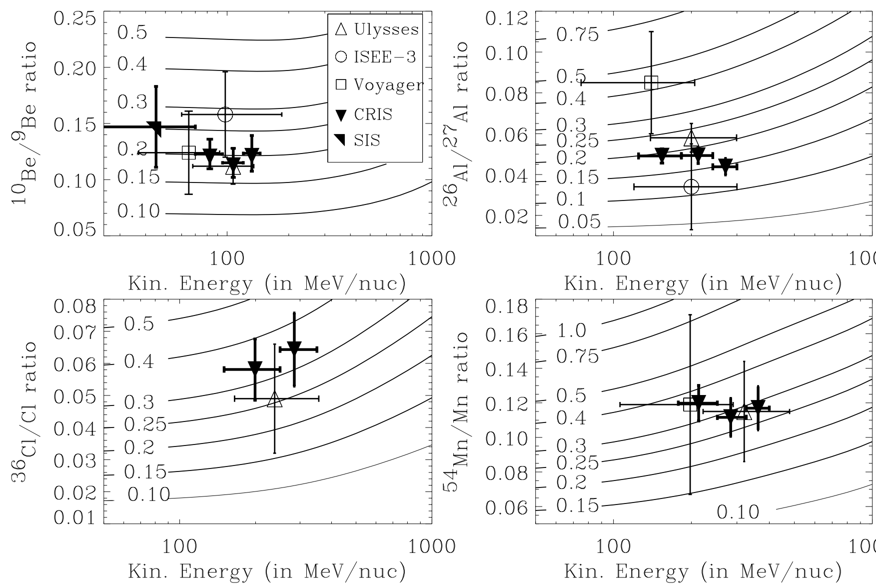

Figure 1: Radioactive clock abundance ratios. Curves show calculated densities of ISM hydrogen (atoms/cm ^{3}). A ^{10}Be data point from the SIS instrument on ACE is shown for comparison. Experiment references can be found in Table 1.

Solar modulation of the cosmic ray spectra was simulated using a spherically symmetric model described by Fisk (1971). The diffusion coefficient was calculated using a specified force-field modulation parameter ϕ ($\sim$ 555 MV for CRIS data, adapted from Badhwar and O'Neill 1993).

3 Discussion:

The clock isotopic abundances are interpreted within the leaky box framework to specify a galactic confinement time. Given a mean pathlength and a confinement time, one can calculate the mean ISM density through which the GCRs propagate, but the clock abundances are sensitive to this time of propagation. The relationship between mean pathlength λ, density ρ, and confinement time τ_{esc} can be written as $\lambda = \rho\beta c\tau_{esc}$. ISM densities derived in this framework should not necessarily be consistent between the various clock species. Cosmic rays diffuse through the galaxy, and given a similar diffusion rate for each species, each clock will sample a volume of the ISM for a time comparable to its decay lifetime. Using the simple relation for diffusion distance

$l = (D\tau_{decay})^{1/2}$ and a typical diffusion coefficient $D \sim 10^{28}$ cm^2 s^{-1} (Ptuskin and Soutoul 1998), ^{10}Be will sample a region within ∼275 pc of the solar system, while ^{36}Cl will sample a smaller region of ∼120 pc. Differences in the average densities derived using each clock should be characteristic of these different surrounding volumes.

Table 1: Mean confinement times of the GCR clock nuclei.

Clock	Experiment*	τ_{esc} (in Myr)†
^{10}Be	ACE/CRIS(this work)	21.0 (+2.4, -1.9)
	Ulysses(Connell 1998)	26.0 (+4.0, -5.0)
	ISEE-3(Wiedenbeck and Greiner 1980)	8.4 (+4.0, -2.4)
^{26}Al	ACE/CRIS(this work)	22.3 (+1.6, -1.5)
	Ulysses(Simpson and Connell 1998)	19.0 (+3.0, -3.0)
	Voyager(Lukasiak et al. 1997b)	13.5 (+8.5, -4.5)
	ISEE-3(Wiedenbeck 1983)	9.0 (+20.0, -6.5)
^{36}Cl	ACE/CRIS(this work)	25.0 (+4.2, -3.4)
	Ulysses(Connell et al. 1998)	18.0 (+10.0, -6.0)
^{54}Mn	ACE/CRIS‡(this work)	29.6 (+2.2, -3.4)
	Ulysses§(DuVernois 1997)	14.0 (+6.0, -4.0)

*Other Voyager results are reported as surviving fractions.
†Quoted errors are statistical.
‡Assumes $\tau_{1/2}$=0.63 Myr. (Wuosmaa et al. 1998)
§Assumes $\tau_{1/2}$=1 Myr.

Figure 1 shows a comparison between radioactive clock abundances measured by recent experiments and our model calculations assuming various interstellar H densities. Data previous to CRIS were reported as one abundance per experiment covering a fairly wide energy range, owing to the limited statistical accuracy. Because of the larger number of events, CRIS data can be plotted at multiple energies and compared to the predicted energy dependence. For direct comparison, the previously reported abundances have been adjusted to the solar modulation level relevant to CRIS. To within statistical uncertainties, the CRIS data are consistent with previous experiments, and density predictions from this model ($\rho \sim 0.15 - 0.4$ H atoms/cm^3) are comparable to results from the Ulysses group (Connell 1998).

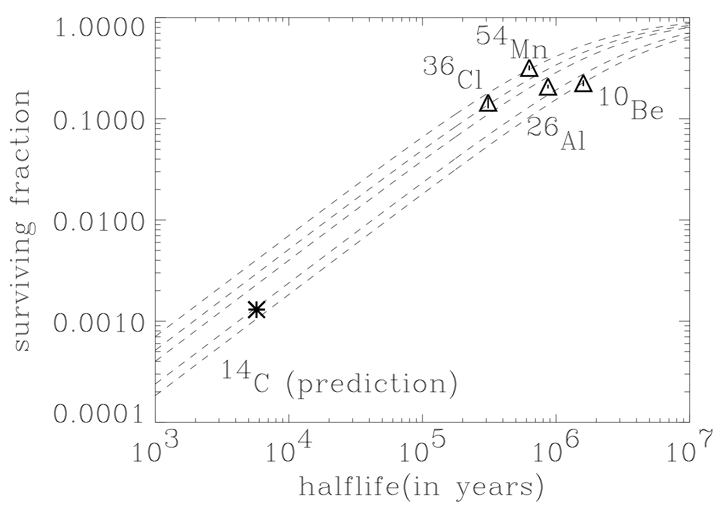

Figure 2: Surviving fraction of clock isotopes. Curves are model predictions from ^{10}Be abundance.

Interpretation is complicated by observed inhomogeneities in the local ISM. The predicted densities are lower than the average galactic disk density of ∼1 atom/cm^3, which may imply significant propagation in a galactic halo of lesser density. However, this could also indicate a substantial amount of propagation in a local ISM cavity (Ptuskin and Soutoul 1998). The ^{36}Cl abundance is suggestive of a higher local ISM density than the longer-lived species indicate, but the difference is not significant. The energy dependences of the clock abundances shown in this propagation model are not inconsistent with the data, although they are not clearly indicated either. Both the energy dependence and the value of the calculated density are dependent on the chosen mean pathlength parameterization, which is different for the sub-Fe/Fe and lower-Z ratios.

The confinement time is less reliant on the parameterization of the mean pathlength than the average ISM density. Using an ISM density appropriate for each species, the confinement times calculated from the CRIS clock abundances are presented in Table 1, along with previous experimental results. Considering the large uncertainty in the halflife of ^{54}Mn ($\sim$ 40%, from Wuosmaa et al. 1998), CRIS predicts a confinement time of τ_{esc} $\sim$22$\times$10^6 years which is consistent with all species. The confinement times obtained from our model calculations are comparable to recent Ulysses results, but they yield somewhat longer times than ISEE-3 results and earlier calculations (e.g., Garcia-Munoz et al. 1981). This may be a result of other experimental groups using different mean ISM pathlengths to calculate the confinement time, originating from earlier measurements of the fragmentation partial cross sections.

The surviving fraction for each clock is shown in Figure 2. A comparison of these with the predictions of Ptuskin and Soutoul's model yields a local diffusion coefficient D ranging from $2 \times 10^{28} - 10^{29}$ cm^2 s^{-1}. Assuming a consistent value of D for all clock species, ^{26}Al and ^{36}Cl abundances do not appear to support simple galactic models composed of a single gas layer or a thin layer, but these are not ruled out for higher values of D. The surviving fraction of ^{14}C is a discriminating test of these models and the value of D. CRIS should record $\sim$ 30 ^{14}C events during a 2 year period, assuming a mean ISM density consistent with other clock abundances (Stone et al. 1999). Whether these few events ($\sim 5 \times 10^{-4}$% of total carbon) can be distinguished from background is under investigation.

4 Conclusions:

Within the context of our leaky-box model, we find a confinement time from CRIS data of $\tau_{esc} \sim$ 22$\times$10^6 years which is consistent for all species. This time is characteristic of a mean ISM H density between 0.15 and 0.40 atoms/cm^3, assuming our parameterization of the mean pathlength. The surviving fractions for all clock species imply a local diffusion coefficient from Ptuskin and Soutoul's model ranging from $2 \times 10^{28} - 10^{29}$ cm^{2}s^{-1}.

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