THE GALACTIC COSMIC RAY ^{36}CL CLOCK: *ULYSSES* HET RESULTS

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ABSTRACT

Radioactive ^{36}Cl, with a β^- lifetime of 3.08×10^5 years, is used to determine the average interstellar density seen by the cosmic rays and the cosmic ray confinement time in the Galaxy. This is the first such determination using ^{36}Cl—previously only limits were possible due to the low statistics and the high mass resolution needed. The density is found to be 0.39±0.15 atoms·cm^{-3}. The confinement time for the cosmic rays, deduced from this density, and the pathlength distribution which fits the *Ulysses* High Energy Telescope (HET) elemental data, is 11±4 Myr. This estimate of the confinement time is generally consistent with results from measurements of radioactive ^{10}Be and ^{26}Al.

INTRODUCTION

The escape time of the galactic cosmic rays is of great importance both for understanding the cosmic rays and for expanding our knowledge of the Galaxy in general. For the cosmic rays, the escape time is a measure of the "leakiness" of the leaky box and a clue to the source of the cosmic rays (Waddington 1977). In the larger picture, dating the cosmic rays, combined with information on the composition of the source, constrains models of Galactic chemical evolution. The time scale of the cosmic ray confinement also directly yields the accelerator input power required to maintain cosmic ray equilibrium in the galaxy (Ginzburg and Syrovatskii 1964)—about 10^{40} ergs/s for cosmic ray confinement times of $\sim 10^7$ years.

The density of the interstellar medium (ISM) through which the cosmic rays traverse is equally important. Since the Galactic disk average density is about 1 atom·cm^{-3}, and all determinations of the density "seen" by the cosmic rays are significantly less, (Simpson and Garcia-Munoz 1988; see also review in DuVernois 1997), it is apparent that the cosmic rays do not simply "bounce around" in the galactic disk. Theories exist in which the cosmic rays spend part of their confinement time trapped in an extended Galactic halo or concentrated in regions of low density within the disk (Parker 1976). At present it is unclear exactly to what regions the cosmic rays are confined, but certainly, for some fraction of the time, it is to regions of lower than average density.

The density and escape time determinations have previously been made using ^{10}Be and ^{26}Al as a clock (Garcia-Munoz, Mason, and Simpson 1977, Wiedenbeck and Greiner 1980, Wiedenbeck 1983, Simpson and Garcia-Munoz 1988, Lukasiak et al. 1994, Lukasiak, McDonald, and Webber 1994). When the theory of cosmic ray chronometers was developed, it was known that in addition to those two, ^{36}Cl and ^{54}Mn are also suitable clocks (Cassé 1973). A lack of mass resolution and statistics had made these measurements previously difficult. For ^{36}Cl, there has been one upper limit on the density (lower limit on the confinement time) published (Wiedenbeck 1985). The use of ^{54}Mn is complicated by the fact that its partial β^- decay half-life has not been measured in the laboratory. Work on ^{54}Mn has been performed using the *Ulysses* HET—these measurements can be found elsewhere (DuVernois 1997).

Chlorine has three isotopes seen in the Galactic cosmic rays. Of these, ^{35}Cl and ^{37}Cl are stable and are seen in the solar system with fractional abundances of 76% and 24% respectively.

The remaining isotope, ^{36}Cl, is unstable with a half life of 3.01×10^5 (98.2% β^-, 1.8% electron-capture decays). In the high-energy cosmic rays, the nuclei are stripped of all of their electrons, suppressing the electron capture reaction and leaving just the β^- channel.

INSTRUMENT & MODEL

The University of Chicago HET is onboard the *Ulysses* spacecraft which was launched in October of 1990 (complete instrument information can be found in Simpson et al. (1992)). The HET consists of six thin position-sensitive silicon detectors (PSDs) and six thick silicon detectors. Analyzed events stop in the thick detectors, have reconstructable, straight-line trajectories in the PSDs, and leave energy in all of the detectors in a consistent manner. Charge and mass are determined using a partial energy-loss versus total energy technique (Bethe-Bloch) averaged and weighted over all detector combinations. Cuts are made to ensure consistency of the mass determination using each of the different detector combinations. The resulting data extends from protons through the iron-nickel group with mass resolution equal to or better than any previous satellite experiment (Simpson 1983, DuVernois et al. 1996) and steadily increasing statistics.

The model of cosmic ray propagation used here is the standard leaky box model, which we solve using the weighted slab technique. This technique is documented elsewhere (Fichtel and Reames 1968, Garcia-Munoz et al. 1987, DuVernois 1997), but in essence, it consists of a set of equations, one for each propagated species, tracking the energy-loss, nuclear spallation, and radioactive decays which are solved as a function of pathlength. These functions are then integrated over the pathlength distribution (PLD) to obtain the local interstellar spectrum. The PLD is experimentally determined by measuring the energy-dependence of the secondary to primary cosmic ray elements (such as boron/carbon and sub-iron/iron). The PLD used in this work is a single exponential pathlength distribution with the energy-dependent mean of Garcia-Munoz et al. (1987) and verified with Ulysses data (DuVernois, Simpson, and Thayer 1995, 1996).

Modulation in the heliosphere is treated as a spherically symmetric solution to the Fokker-Planck equation (Fisk 1971). The spherical symmetry was shown to be an accurate approximation by the helio-latitudinal study of *Ulysses* data (Simpson et al. 1995). The level of modulation is characterized by the force-field parameter ϕ for convenience. For the Ulysses data used in this paper, an event-weighted average ϕ of 800 MV was determined from the IMP-8 high energy helium data (Garcia-Munoz, Pyle, and Simpson 1985) matched with the event timing. The IMP-8 determination is in good agreement with the Climax neutron monitor measurements (Badhwar and O'Neill 1993) over the same time period. All propagation calculations are performed for this level of solar modulation.

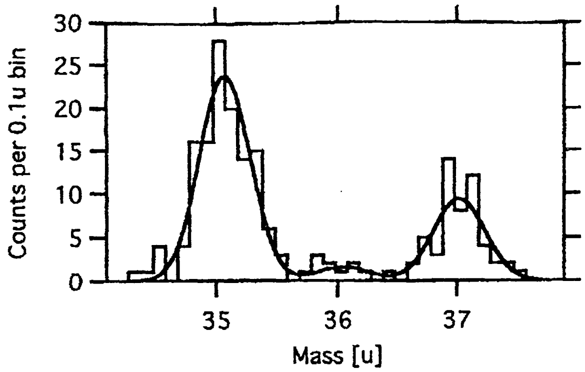
DATA & ANALYSIS

The ^{36}Cl/Cl ratio is sensitive to the density of the interstellar material through which the cosmic rays traverse. The fraction of a radioactive isotope which survives is a function of the time in flight, but with a fixed total pathlength, this is a measure of the density. The pathlength, λ_{esc}; interstellar density, ρ; flight distance, X; velocity, βc; and escape-time, T_{esc} are related by

$$\lambda_{esc} = \rho X = \rho\beta c T_{esc}. \quad (1)$$

The density of the interstellar medium to the cosmic rays is found from fitting the *Ulysses* HET data. The velocity is determined from the experimental energy determination which is extrapolated to local interstellar space outside the heliosphere. For an extrapolated energy of 425 MeV/nucleon in the ISM, this velocity is 0.71c. The pathlength is determined by the secondary to primary elemental measurements and is about 6.2 g/cm^2 at this energy.

Looking at the *Ulysses* HET data, we find eleven ^{36}Cl events. The isotope histogram for



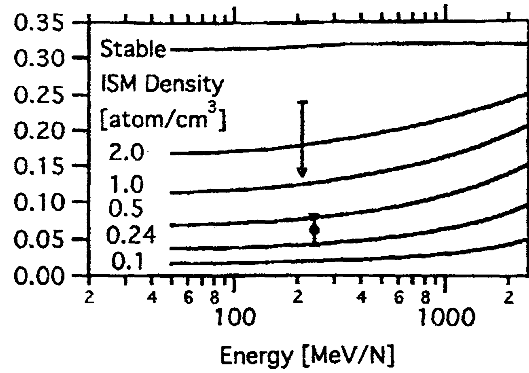


Fig. 1: (Left) Ulysses chlorine isotopes (data and maximum likelihood fit).
Fig. 2: (Right) ^{36}Cl/Cl ratio: curves, propagation for various ISM densities; open circle, Ulysses HET; upper limit, ISEE-3 (Wiedenbeck 1985).

chlorine is shown in Figure 1. The experimental ^{36}Cl/Cl ratio is 0.064±0.020 at an energy of 240 MeV/nucleon. The propagation calculation results for interstellar densities of 0.1, 0.24 (the "nominal" value), 0.5, 1.0, 2.0, and 10^9 (equivalent to no radioactive decays) atom·cm^{-3} are also show. (Curves are calculated for every 0.05 atom·cm^{-3} up to 2.0.) There is assumed to be no ^{36}Cl at the source—it would have decayed away prior to acceleration. The data point and the results of the propagation appear in Figure 2.

The best fit for the density, going through the data point, is 0.39±0.15 atom·cm^{-3}, determined by interpolation of the propagation curves. Using Equation 1 with this density, the local interstellar velocity of cosmic rays of this energy, and the pathlength distribution (determining λ_{esc}) gives the cosmic ray escape (or confinement) time. This time period is 11±4 Myr. The errors are estimated by using the density errors and folding in uncertainties in the velocity before entry into the heliosphere. Other determinations of the cosmic ray propagation time can be seen in Table 1.

Table 1: *Density and confinement time measures for the Galactic cosmic rays.*

Isotope	ρ [atoms·cm^{-3}]	CR life-time [Myr]	Reference
^{10}Be	0.18 (+0.18,-0.11)	17 (+24,-8)	Garcia-Munoz, Mason, and Simpson '77
	0.30 (+0.12,-0.10)	8.4 (+4.0,-2.4)	Wiedenbeck and Greiner '80
	0.23 (+0.13,-0.11)	14 (+13,-5)	Garcia-Munoz, Simpson, and Wefel '81
	0.24±0.07	15 (+7,-4)	Simpson and Garcia-Munoz '88
	0.28 (+0.14,-0.11)	27 (+19,-9)	Lukasiak et al. '94
	0.23±0.04	18±3	Connell '97
^{26}Al	0.28 (+0.72,-0.19)	9 (+20,-6.5)	Wiedenbeck '83
	0.52 (+0.26,-0.20)	13.5 (+8.5,-4.5)	Lukasiak, McDonald, and Webber '94
	0.28 (+0.05,-0.04)	15.6 (+2.5,-2.6)	Connell and Simpson '97
^{36}Cl	limits	limits	Wiedenbeck '85
	0.39±0.15	11±4	This work
^{54}Mn	0.37 (+0.16,-0.11)	14 (+6,-4)	DuVernois '97

N.B.: Adapted from DuVernois 1997. These are the quoted, published, confinement times—using a different PLD would alter these values somewhat. Mn confinement is for an assumed ^{54}Mn β^- partial half-life of 1 Myr.

CONCLUSIONS

The cosmic ray ^{36}Cl clock is consistent with the results of measurements with ^{10}Be and ^{26}Al. The density seen by the cosmic rays is lower than the Galactic disk average of 1 atoms·cm^3 and the cosmic ray escape time is on the order of $\sim 10^7$ years. From the density measurement, the observation that the cosmic rays must spend part of their confined time in regions of low density is confirmed. If the magnetic fields in the extended Galactic halo are sufficiently strong, this could be the site of the confinement.

The different absolute values of the escape times as seen in Table 1 are due primarily to the different pathlengths used in the various analysis schemes. There remains considerable uncertainty in the confinement time and density. Using the same propagation parameters, simultaneous *Ulysses* measurements of the ^{10}Be, ^{26}Al, and ^{54}Mn clocks (Connell 1997, Connell and Simpson 1997, and DuVernois 1997), along with this ^{36}Cl work, have been performed. These measurements are in reasonable agreement with each other.

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