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Galactic cosmic ray response to heliospheric environment changes and implications for cosmogenic isotope records

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Changes in the local interstellar environment of the Sun due to its encounters with interstellar clouds of different densities are an important source of long term cosmic-ray variability as measured in cosmogenic isotope records. We present a systematic study of the dependence of galactic cosmic ray intensity in the solar system on the changing background conditions of the heliosphere. We compare three different scenarios: the tenuous fully ionized Local Bubble, the Local Interstellar Cloud, and a dense cold cloud of pure atomic hydrogen. Using several plausible models of interplanetary turbulence production and transport we investigate the dependence of the cosmic-ray mean free paths and intensities on the size of the modulation region and the pickup-ion intensities. Our calculations show that cosmic-ray intensities below 1 GV rigidity could vary by more than a factor of 4 between extreme cases resulting in a range of variation in ^{10}Be rates between a 25% decline in low-density environments to an increase in excess of 300% in high density clouds compared to current levels.

1. Introduction

The solar system is currently embedded in a diffuse partially ionized Local Interstellar Cloud (LIC) with an average density of $\sim 0.34\,\mathrm{cm}^{-3}$ and temperature of about 7000 K. The heliospheric interface results from the interaction of the solar wind (SW) with the material of the cloud streaming past the solar system at ~ 25 km/s. The Sun probably entered the LIC some 10^5 years ago. Prior to this event our interstellar environment was that of the Local Bubble (LB), a galactic region with anomalously low density ($< 0.005\,\mathrm{cm}^{-3}$) but high temperature ($T \sim 10^6$ K) and degree of ionization. During its journey through the Galaxy the Sun has also encountered high density interstellar clouds. There is evidence that the so-called G cloud, which could become the next solar environment in another 10^3–10^5 years, may be 15 times denser than the LIC [4].

Changes in the interstellar environment would have a dramatic effect on the heliosphere. The region expands in low density environments and contracts when the ambient density is high. This implies that the properties of the heliospheric interface as a medium for galactic cosmic ray (GCR) propagation also vary with time. A thicker heliosheath is expected to filter a larger fraction of the galactic radiation reaching Earth. In addition, more charge exchange will occur in the SW when the neutral hydrogen density inside the cloud is high, resulting in higher pickup ion production rates and, consequently, more turbulent conditions in the SW which would accordingly increase the amount of modulation.

Cosmogenic isotopes, such as ^{10}Be, provide records of GCR intensities over the past 10^4–10^6 years. These records show significant variability on virtually all timescales. Perhaps the best known are the two prominent peaks occurring some 35,000 and 60,000 years ago when the flux of cosmic rays reaching Earth was more than two times the present value [6]. Much of the short-term variability can be explained by changes in solar activity, while longer-term variations appear to correlate with changes in the Earth's magnetic dipole. As shown in [8, 2] a small (0.05 pc) but dense interstellar cloud passing the solar system would have had a similar effect and the resulting GCR intensity increase at Earth would be sufficient to explain the peaks. This paper provides a brief summary of our effort to model variations in GCR fluxes due to changes in the underlying structure of the heliosphere driven by variable interstellar environments. A more comprehensive account can be found in [1].

2. Modeling the transport properties of the heliosphere

The present model is built upon the cosmic ray transport framework developed for the global heliosphere, including the heliosheath region [3]. A multi-fluid MHD-neutral numerical code is used to compute the plasma flows and heliospheric magnetic field in the meridional plane (the plane containing the apex direction and the solar polar axis). To find the diffusion coefficients we use the standard quasi-linear expression for $\kappa_\parallel$ and the nonlinear guiding center result for $\kappa_\perp$ [5, 10]. In particular,

$$\kappa_\parallel = \frac{w r_g^2 B^2}{8\pi} \int |\mu|(1-\mu^2) P_{xx,sl}^{-1}(1/|\mu| r_g) d\mu, \tag{1}$$

$$\kappa_\perp = C(\langle \delta B_{2D}^2 \rangle / B^2)^{2/3} l_c^{2/3} \lambda_\parallel^{1/3}, \tag{2}$$

where w is the particle velocity, r_g is the gyroradius, μ is the pitch angle cosine, $\lambda_\parallel$ is the parallel mean free path, $\langle \delta B_{sl,2D}^2 \rangle = \int P_{xx,sl,2D} dk$ is the magnetic field variance in the slab and 2D components, l_c is the associated correlation length, and C is a numerical constant. The quantity $P_{xx,sl,2D}$ is the spectral power density of the slab and 2D turbulence and Eq. 1 expresses the resonant scattering condition. In the outer heliosphere GCRs resonate in the energy-containing turbulent range and the diffusive properties of the interface are sensitive to the spectral shape in this region. To cover a range of possibilities we consider two models with a flat energy range (model 1) and with $P_{xx} \sim k^{-1}$ (model 2).

To find $\langle \delta B^2 \rangle$ and l_c throughout the heliosphere we use the Bartol model of incompressible axisymmetric turbulence transport in the solar wind [9]. The turbulent content of the SW is influenced by the presence of shear flows and compression/expansion as well as wave excitation by the pickup process. The latter is proportional to the charge exchange rate which is easily obtainable from the plasma-neutral model. Because the theory does not extends to the hot subalfvénic conditions found in the heliosheath, we employ the expression for Alfvén wave transmission through a quasi-perpendicular shock and keep the turbulent ratio constant in the region downstream of the TS.

3. Interstellar environment changes and cosmic-ray response

We evaluate three models characteristic of the present environment (LIC), the tenuous LB and a hypothetical dense cloud (DC). Boundary conditions and the model-derived interface properties are summarized in Table 1. In the LB the TS is located at approximately the same heliocentric distance as it is now in the apex direction, and is nearly spherical in shape. The major difference is that the heliosheath is nearly three times thicker in the LB. Since pickup ions are not produced, the only source of turbulence is stream interactions, which are ineffective beyond several AU. The wave intensity decreases as $\langle \delta B_x^2 \rangle \sim r^{-7/2}$ resulting in a rapid increase of

Table 1. Summary of interstellar environments. $N_{\mathrm{t}\,\infty}$, T_∞, and V_∞ are the total hydrogen density (H+H$^+$), temperature and speed of the cloud relative to the Sun, respectively, and η is the ionization ratio. Model-derived quantities listed are the distance to the TS (r_{TS}), the relative thickness of the heliosheath h, and the TS compression ratio s.

Model	$N_{\mathrm{t}\,\infty}$, cm^{-3}	η	T_∞, K	V_∞, km/s	r_{TS}, AU	h	s
Local Bubble (LB)	0.005	1.0	1.2×10^6	12.5	100	0.5	3.1
Local Interstellar Cloud (LIC)	0.21	0.33	7000	25	100	1.8	4.0
Dense Cloud (DC)	10	0.0	200	25	12	1.0	1.6

the diffusive mean free path with radial distance (cf. the LIC and LB panels in Figure 1). However, the drop in λ_{rr} across the TS is also larger due to a larger shock compression ratio and the dominance of parallel diffusion in the LB case, which has a stronger dependence on $|\mathbf{B}|$ than cross-field diffusion (cf. Eqs. 1 and 2).

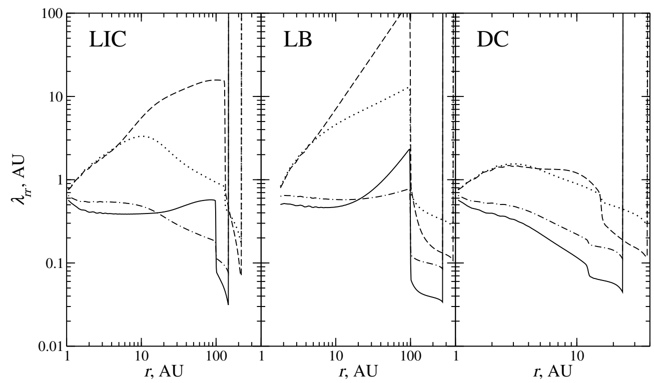

Figure 1. Radial diffusive mean free path of 1 GeV protons. Solid lines correspond to ecliptic and dashed to high latitudes in mode 1, while dot-dashed and dotted lines refer to model 2 results at the same latitudes.

Figure 2 demonstrates the effect of the interstellar environment on GCR modulation by the heliosheath only (left) and the entire heliospheric interface (right). The heliosheath modulation is more dominant (85% and 54% of the total at 1 GeV for models 1 and 2, respectively, compared with 52% and 25% for the LIC). Unlike the LIC case, model 2 actually predicts a higher GCR intensity at 1 AU than model 2, which is a consequence of the diffusion coefficient being quite large in the SW in both models, whereas the LIC model 2 predicts small SW diffusion. It follows then that GCR proton fluxes above 300 MeV at Earth when the Sun was embedded in the LB could have been either higher or lower than at present, depending on which of the models is correct.

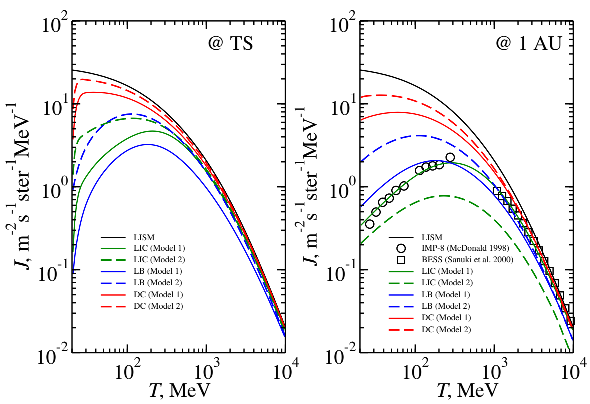

Figure 2. Spectra of GCR protons at 1.1 the distance to the TS in the apex direction (left panel) and at 1 AU (right panel) for the three interstellar environments described in the text.

In the opposite case of a dense cloud, pickup ions are produced in abundance enhancing the rate of turbulent driving in the SW. As a result, proton mean free paths are generally smaller in the SW than in the LIC, but

Table 2. ^{10}Be production rate relative to the present rate as a function of the interstellar environment and diffusion model.

Galactic environment	Model 1	Model 2
Local Interstellar Cloud (LIC)	100%	100%
Local Bubble (LB)	77%	219%
Dense Cloud (DC)	134%	330%
No modulation	175%	407%

experience a smaller decrease across the TS because of a smaller shock compression ratio and the prevalence of cross-field mode of transport. The radial mean free path in the heliosheath is actually larger than in the LIC. The combined effects of a relatively large heliosheath κ_{rr} and a much smaller extent of the modulation cavity is a significant reduction in the heliospheric shielding of GCRs. Figure 2 shows that the intensity between 300 MeV and 1 GeV is increased by a factor of 1.4–2.4 in model 1 and by a factor of 4.1–7.6 in model 2.

4. Conclusions: cosmogenic isotope production

Long-lived radioactive isotopes, such as ^{10}Be, are produced in air showers caused by the passage of highly energetic cosmic ray ions (mostly protons) through the Earth's atmosphere. The production rate is

$$P = \int_0^\infty S(T) \frac{dJ}{dT} dT, \tag{3}$$

where $S(T)$ is the specific yield of the product isotope from the primary particle with a kinetic energy T [7] and dJ/dT is the primary proton spectrum at 1 AU plotted in Figure 2.

The results of the calculation for the two turbulence models are summarized in Table 2. Model 1 predicts a relatively modest amount of variability. The LB environment shows a modest reduction in the ^{10}Be production rate, while the DC shows a somewhat larger increase. The variations are significantly larger in model 2. Both the LB and DC exhibit less modulation in this model and ^{10}Be production rates are increased by a factor of 2–3. The last line in Table 2 refers to a hypothetical cloud with a density so high that the heliosphere is compressed to the size of the Earth's orbit or less and the amount of modulation at 1 AU is effectively zero. It is seen that the largest possible increase in the rate of cosmogenic isotope production due to galactic environment variability is in the range of 75–300%. This is certainly enough to explain the variability measured in ^{10}Be records.

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