Abstract

Galactic cosmic rays are believed to play a role as contributor to ozone layer chemistry, biological mutation rates, and climate. The solar wind modulates the low-energy Galactic cosmic-ray flux in our solar system, but this modulation depends on the size and other properties of the heliosphere and the details of cosmic-ray propagation. It has been suggested for decades that the cosmic-ray flux on Earth, and presumably other habitable planets, should be greatly enhanced when the Sun traverses interstellar clouds and reduced when it passes through voids, yet the frequency and duration of such events remains very uncertain. We attempt to quantify the problem by using simulations of the heliosphere moving through two sets of interstellar medium models. (1) A 3D MHD simulations, with temporal resolution spanning ~10^5-10^9 years, and (2) a new absorption line observations of gas toward local stars. Here we describe an experiment and observing program to compare our recent interstellar volume density history with existing geological records to directly explore the link between our astronomical environment and the cosmic-ray flux incident on the Earth’s atmosphere.

Introduction

The interstellar medium (ISM) is a dynamic and complex environment, which ensures the Sun, and our solar system, have encountered a wide range of conditions. At the top of the poster is a map of the carbon monoxide (CO) distribution along the solar system’s trajectory (from Lallement et al. 2003, Astr. Astrophys.: J.). Dark shadings indicate high density material. The Sun is roughly located in the center of the Local Bubble, a cavity devoid of gas and dense material. Dense environments are only ~10^3-10^4 pc distant, which means the Sun has passed (or will pass) through them in ~10^6 yr. The recent interstellar cloud encounters trace the past and future solar paths, respectively. The time required to traverse the length of each arrow is ~13 km s^-1 (Dennison & Binney 1998, MNRAS). We then convert the variable density profile into a predicted cosmic-ray flux history. Over relatively modest density fluctuations of 1-2 orders of magnitude, the cosmic-ray flux varies by 2-3 orders of magnitude. The extreme variability of the cosmic-ray flux is evident, particularly in the lower-density regions. A dip in the density of roughly three orders of magnitude between 0.2 and 0.5 Myr becomes a flux reduction of ~10^0. Note that at densities above about 10^1 cm^-3, the fluctuations in the cosmic-ray flux are damped due to the saturation effect of demodulation. The acceleration of dust and gas into the solar system could still vary significantly, however, as this is a different process time than is discussed here.

Passage through an Interstellar Cloud

First we studied the cosmic-ray variations due to passage of the solar system through a molecular cloud whose average density is large enough to result in complete demodulation of cosmic rays by pushing the heliosphere inside of 1 AU. The time in the past when such an event last occurred is very uncertain because the Sun’s current molecular cloud encounter is quite close to the Sun’s recent relative heliopause. We model the time series of terrestrial cosmic-ray fluxes and estimate the probability distribution of cosmic-ray fluxes and associated durations. We show that, during an interstellar cloud passage, cosmic-ray flux enhancements that occur through the simulated cloud with average density 30 cm^-3. The 10-MeV cosmic-ray flux is presented relative to the present-day level. The extreme variability of the cosmic-ray flux is evident, particularly in the lower-density regions. A drop in the density of roughly three orders of magnitude between 0.2 and 0.5 Myr becomes a flux reduction of ~10^0. Note that at densities above about 10^1 cm^-3, the fluctuations in the cosmic-ray flux are damped due to the saturation effect of demodulation. The acceleration of dust and gas into the solar system could still vary significantly, however, as this is a different process time than is discussed here.

Figure 2: High-resolution time series of densities and cosmic-ray fluxes encountered on a sampled trajectory through the simulated cloud with average density 30 cm^-3. The 10-MeV cosmic-ray flux is presented relative to the present-day level. The extreme variability of the cosmic-ray flux is evident, particularly in the lower-density regions. A drop in the density of roughly three orders of magnitude between 0.2 and 0.5 Myr becomes a flux reduction of ~10^0. Note that at densities above about 10^1 cm^-3, the fluctuations in the cosmic-ray flux are damped due to the saturation effect of demodulation. The acceleration of dust and gas into the solar system could still vary significantly, however, as this is a different process time than is discussed here.

Figure 3: Probability distribution of durations and recurrence times for a 10-MeV cosmic-ray flux enhancement ranging from 10 to 100 above present levels. Clouds of two different average densities are modeled: 30 and 300 cm^-3. The lower density cloud was encountered far more frequently, roughly by a factor of 100, than the higher-density cloud, since the frequency of clouds at a given density from various cloud catalogues is a strong inverse power law. Solar effects such as changes in the solar cycle would be even smaller, although the high densities could still lead to intense cosmic-ray fluxes. Note that, for example, in the low-density cloud (30 cm^-3), a cosmic-ray flux enhancement of 10-100 lasting 20,000 yr will occur roughly every 1.4 Myr, while in the high-density cloud, these events occur only every 12.5 Myr. The averages of the histograms give the overall average durations and recurrence times of 10-100 enhancement events inside of these clouds.

Reconstructing our Historical Local Interstellar Environment

We can reconstruct the volume density of our solar system likely encountered over the last 30 Myr years by measuring the distribution and physical characteristics of the interstellar medium along the direction of the Sun’s historical trajectory. This reconstruction will require new astronomical observations involving interstellar optical and UV lines and measuring toward local stars. Here we describe an experiment and observing program to compare our recent interstellar volume density history with existing geological records to directly explore the link between our astronomical environment and the cosmic-ray flux incident on the Earth’s atmosphere.

Figure 4: Using high-resolution spectroscopy, we can measure the physical characteristics of clouds in the ISM. Spectral observations of nearby stars contain information both on the stellar light and absorption from intervening interstellar material (i.e., clouds). Some examples of absorption lines are shown. Modelling the shape of the absorption line provides information on the physical properties of the cloud, including the quantity of gas, temperature, and the presence of turbulence, and depletion onto dust grains. By combining individual observations of numerous stars at various distances along a particular direction, we can reconstruct the line-of-sight density distribution.

Figure 6: The solid black histogram shows an illustrative density profile along the historical solar trajectory. The Galactic interstellar environment along the Sun’s past trajectory. The red histogram indicates our “observed” construction of the density profile given spectroscopic observations of the 100 stars along the historical solar path shown in Figure 5. The illustrative density profile was created with a finite number of discrete clouds of uniform density based on the number density of clouds in the model (Lallement et al. 2003, Astr. Astrophys.). We can then convert the variable density profile into a predicted cosmic-ray flux history. Over relatively modest density fluctuations of ~10^0 cm^-3, the fluctuations in the cosmic-ray flux are damped due to the saturation effect of demodulation. The acceleration of dust and gas into the solar system could still vary significantly, however, as this is a different process time than is discussed here.

Figure 5. The illustrative density profile was created with a finite number of discrete clouds of uniform density based on the number density of clouds in the model (Lallement et al. 2003, Astr. Astrophys.). We can then convert the variable density profile into a predicted cosmic-ray flux history. Over relatively modest density fluctuations of ~10^0 cm^-3, the fluctuations in the cosmic-ray flux are damped due to the saturation effect of demodulation. The acceleration of dust and gas into the solar system could still vary significantly, however, as this is a different process time than is discussed here.

As a model for these cloud complexes we use a 3D, magnetohydrodynamic, numerical simulation of isothermal, supersonic, turbulent clouds kindly provided by P. Paubert. This model agrees with several observed statistical properties of molecular clouds (see Nordlund & Padoan 2003, Lect. Notes Phys.). We scale the model cloud to a size of 150 parsecs and mean total mean number density of both 30 (similar to a typical classical diffuse neutral hydrogen cloud) and 300 cm^-3 (similar to a typical molecular cloud). The (model) cloud possesses complex density and velocity structure spanning several orders of magnitude in density, with spatial scales down to ~0.04 pc (~3000 au).

We track the size of the heliosphere in the apex direction by integrating the solar-wind ram pressure with the fluctuating ram pressure within the cloud (Zank & Frisch 1999, Astrophys. J., including the convective inflow of material underlying the shock front) which dominates the physics at these densities (Bagla & Rees 1973, Nature). We include only ram pressure and ignore magnetic effects for this initial work. We track the cosmic-ray flux using a simplified convection-diffusion model for heliospheric cosmic-ray propagation assuming a radially constant diffusion coefficient calculated from a factor of 100 enhancement in the heliospheric apex distance of 155 AU (Gumett et al. 2003, Geophys. Res. Lett.) in order to build a statistical sample, we passed the solar system through the simulation cube along random trajectories 10^5 times.