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Cosmic rays and climate change over the past 1000 million years

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HIGHLIGHTS

- Cosmic ray intensity over the last billion years is examined.
- Intensity change as solar system moves out of a Galactic spiral arm is studied.
- Using conventional diffusion parameters intensity changes of 10–20% are derived.
- These are too small for the large scale changes in climate proposed by others.
- They are also too small to account for species extinctions as postulated by others.

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ABSTRACT

The Galactic cosmic ray (GCR) intensity has been postulated by others to vary cyclically with a peak to valley ratio of $\sim$3:1, as the Solar System moves from the Spiral Arm to the Inter-Arm regions of the Galaxy. These intensities have been correlated with global temperatures and used to support the hypothesis of GCR induced climate change. In this paper we show that the model used to deduce such a large ratio of Arm to Interarm GCR intensity requires unlikely values of some of the GCR parameters, particularly the diffusion length in the interstellar medium, if as seems likely to be the case, the diffusion is homogeneous. Comparison is made with the existing gamma ray astronomy data and this also indicates that the ratio is not large. The variation in the intensity is probably of order 10–20% and should be no more than 30% as the Solar System moves between these two regions, unless the conventional parameters of the GCR are incorrect. In addition we show that the variation of the GCR intensity, as the trajectory of the Solar System oscillates about the Galactic Plane, is too small to account for the extinctions of species as has been postulated unless, again, conventional assumptions about the GCR parameters are not correct.

1. Introduction

The rate of variation of the GCR intensity over the last 1000 million years (Ma) was investigated by Shaviv (2003, 2002). He deduced from a model that the GCR intensity varies by a factor $\sim$3 and cyclically with a period of 143 Ma as the Solar System moves from the Spiral Arm (SA) to the Inter-Arm (IA) region of the Milky Way Galaxy. This variation was compared with proxies for the global temperature and a correlation observed (Shaviv and Viezer, 2008). This correlation has been used as evidence favouring the contentious claim of a connection between GCR and climate change (Shaviv and Viezer, 2008; Kirkby, 2007; Svensmark, 2007).

Subsequently, it was shown (Overholt et al., 2009) that the crossing of the spiral arms was in fact irregular and that the maximum and minimum GCR intensities deduced by Shaviv (2003, 2002) did not correlate in time with the Solar System crossings of SA and IA regions of the Galaxy. The intensity variation with time was studied from meteorites by Leveille et al. (1999). From this study evidence was presented for an increase in the GCR rate during the last 10 Ma compared with the rate over the range 170–700 Ma (Leveille et al., 1999). However, this result was not confirmed by Ammon et al. (2009). They could not find evidence for a strongly varying GCR rate but their conclusion was based on only two meteorites. Wieler et al. (2011) also could not find evidence for a strongly varying GCR rate from a study of iron meteorites although they did not report a statistical analysis. They used the same sample of the $\sim$80 meteorites reported by Voshage et al. (Voshage and Feldmann, 1979; Voshage (1984)) as Shaviv (2003, 2002), each selecting different subsamples of 38 and 50 meteorites, respectively. All these analyses are based on such small numbers of meteorites and the statistical precision of the data and the accuracy with which meteorite ages can be measured limit the conclusions which can be drawn from such studies.

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In this paper we show, using conventional assumptions of GCR parameters, that the difference in the GCR intensity as the Solar System moves from the SA to IA regions should be much smaller than that deduced by Shaviv. We use the data from gamma ray astronomy to confirm these findings. We go onto show that, unless GCR diffusion properties of the Galactic Interstellar medium are very different from their conventional form, GCR are unlikely to be associated with large scale climate changes such as the ice age epochs of the last billion years.

2. Cosmic ray variations over spiral Arm/Inter-Arm transits.

2.1. The spiral geometry of the galaxy.

The conventional picture of our Galaxy, the Milky Way, (and many other galaxies) is that it has spiral arms, these being regions where new star formation mainly takes place. In turn, short lived massive stars which later explode to form Type 2 Supernovae (SN), are mainly found in the Arms. Such SN remnants are generally thought to be responsible for the production of GCR with a differential injection energy spectrum falling as E^{-n}, with spectral exponent $n \simeq 2.15$ up to energies $E \sim 10^{15}$ eV. The current view is that the extra star formation is caused by the increased gas pressure in the Arms from the spiral density wave. In the present vicinity of the Solar System, the centre lines of the SA are separated by about 1.7 kpc between the Local Arm and the neighbouring Sagittarius–Carina arm (Gies and Helsel, 2005 and Vallée, 2005).

Separations between the SA nearer the Galactic Centre and in the far Outer Galaxy vary somewhat in the range 1.7 to 3 kpc. The variability arises from the inevitability of a non-perfect spiral wave, the gas density being non-uniform in the pre-Galactic environment, together with tidal shear from other galaxies. The adopted form of the Spiral Arms at present comes from optical and radio measurements of stars and gas as a function of Galactic longitude and latitude.

Examining the distributions of the positions of SN remnants shows that they are roughly distributed about the the centre lines of the SA as Gaussian shapes with probable long tails. Such long tails will reinforce our conclusions of a small difference in the Galactic GCR intensity between the IA and SA. However, we make the conservative assumption of a Gaussian shape in what follows. The spatial distribution of Type 2 SN has been determined (Bartunov et al., 1994) to have a half-width at half maximum of ~0.7 kpc along a Galactic radius, i.e. approximately a Gaussian with standard deviation of ~0.6 kpc.

2.2. Model predictions for the ratio of the IA and SA GCR intensities.

2.2.1. General aspects

To a first approximation one can assume that GCR are produced randomly in time and space in the SA but modulated by the radial distribution described in Section 2.1. The GCR then diffuse with a spatially independent diffusion coefficient. Such a model is that used previously by us (e.g. Erlykin et al. (2003)), although without an SA/IA modulation. In that work a GCR scale height of 1 kpc was adopted. This is an important parameter in diffusion theory and is discussed in detail in Section 2.2.2.

For a separation of the Arms (radially) of d, and a standard deviation equal to the scale height, σ, the GCR intensity, I, at the centre of one of several parallel equally spaced Arms will be, (adding the contributions from neighbouring arms):

$$I(SA) = G(\sigma, 0) + 2G(\sigma, d) + 2G(\sigma, 2d) + \cdots, \tag{1}$$

where $G(\sigma, x) \propto \exp -(x - \bar{x})^2 / 2\sigma^2$ is the Gaussian function of x about its mean $\bar{x}$. Similarly, the GCR intensity at the centre of the IA will be:

Table 1
Calculated deficits for different values of scale height, σ (standard deviation of particle diffusion) and d the radial separation of the Spiral Arms.

σ (kpc)	d (kpc)	deficit (δ%)
1	2	3
1	3	36
2	2	0
2	3	0.1

$$I(IA) = 2G(\sigma, 0.5d) + 2G(\sigma, 1.5d) + 2G(\sigma, 2.5d) + \cdots \tag{2}$$

Estimates of the differences in the GCR intensities, $I(IA)$ and $I(SA)$, based on Eqs. (1) and (2) are given for different values of d and σ in Table 1. These are expressed as deficits, δ, given by,

$$\delta = 1 - \frac{I(IA)}{I(SA)}. \tag{3}$$

The rather small calculated deficits occur because the Inter-Arm separations are of similar magnitudes to the scale heights, σ (see Section 2.2.2). The conclusion from Table 1 is that only for SA separated by more than 2.5 kpc would we expect a deficit of more than 20%. A detailed comparison with the experimental data will be given later.

Keeping with our simple model (of constant diffusion coefficient, etc.) attention can be drawn to the calculations of Erlykin et al. (2003) in which different modes of propagation were considered and expected proton spectra were estimated for randomly distributed SN in space and time, the GCR being assumed to come from the subsequent supernova remnants. Spiral Arm features were not considered but the spread of predicted spectra would correspond to different local locations of the SN. At GeV energies the range of predicted intensities was ±20% for normal diffusion and ±30% for ‘anomalous’ diffusion. The lower extreme values will correspond roughly to the Spiral Arm modulation situation so, again, a deficit of about 20% is indicated. This value is of the same order as those indicated in Table 1.

2.2.2. The cosmic ray scale height

The scale height, σ, is defined as the distance from the median Galactic Plane at which the GCR intensity falls to a fraction $e^{-1/2}$ of its mid-Plane magnitude. The value is a convolution of the standard deviation of the source distribution (~0.6 kpc for super-novae, see Section 2.1) and and the diffusion length of the produced GCR from the sources. It is appreciated that the distribution may not be accurately Gaussian (see Section 2.1 and later) but it is usually assumed to be so. Many analyses give values of σ from 1 to 2 kpc but others give larger values (e.g. Moskalenko et al. (2004) give 4–6 kpc). It can be seen from Eqs. (1) and (2) that the deficits decrease rapidly as the scale height increases.

In view of the standard deviation of the SN distribution being 0.6 kpc (see Section 2.1) it would be impossible for σ to be less than this. Much higher values than 1 kpc are not ruled out, however: explanations for the small ’Galactic gradient’ of the GCR intensity, particularly in the Outer Galaxy, i.e. for Galactocentric distances greater than that for the Sun at radius 8.5 kpc, include the possibility of a big scale height (e.g. Erlykin and Wolfendale (2011), and earlier references therein). Indeed, Strong et al. (2004) suggest a value as high as 20 kpc. However, this could be due to the existence of a 2-component Halo with the Outer, low density region having the very large scale height. The GCR intensity distribution above and below the Plane could then still be close to that for σ = 1 kpc.

Hunter et al. (1997) fitted a comprehensive GCR propagation model to the EGRET data on the measured cosmic ray gamma ray intensities. The fit gave a GCR scale height of 1.8 kpc. A useful