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COSMIC RAYS AND CLIMATE CHANGE OVER THE PAST 1000 MILLION YEARS

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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 (Shaviv 2003). 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 Veizer 2008). This correlation has been used as evidence favouring the contentious claim of a connection between GCR and climate change (Shaviv and Veizer 2008, Kirkby 2007, Kirkby 2012, 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 (Shaviv 2003) 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

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varying GCR rate but their conclusion was based on only two meteorites. Wieler et al (2010) 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 ~80 meteorites reported by Vosage et al (Vosage 1979 and Vosage 1984) as Shaviv (Shaviv 2003), 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.

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 on to 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 $n \approx 2.15$ 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 Vallé 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 (eg Erlykin and Wolfendale, 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, $\sigma$, the GCR intensity, $I$, at the centre of one of several parallel equally spaced Arms will be, (adding the contributions from neighbouring arms):

$$I(SA) = G(\sigma, 0) + 2G(\sigma, d) + 2G(\sigma, 2d) + ..., \quad (1)$$

where $G(\sigma, x) \propto \exp \left( -\frac{(x - \bar{x})^2}{2\sigma^2} \right)$ is the Gaussian function of $x$ about its mean $\bar{x}$.

Similarly, the GCR intensity at the centre of the IA will be:

$$I(IA) = 2G(\sigma, 0.5d) + 2G(\sigma, 1.5d) + 2G(\sigma, 2.5d) + ......... \quad (2)$$

Estimates of the differences in the GCR intensities, $I(IA)$ and $I(SA)$, based on equations (1) and (2) are given for different values of $d$ and $\sigma$ in table 1. These are expressed as deficits, $\delta$, given by,

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

**Table 1**

| $\sigma$(kpc) | $d$(kpc) | deficit(%) |
|----------------|---------|------------|
| 1              | 2       | 3          |
| 1              | 3       | 36         |
| 2              | 2       | 0          |
| 2              | 3       | 0.1        |

The rather small calculated deficits occur because the inter-arm separations are of similar magnitudes to the scale heights, $\sigma$ (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 and Wolfendale (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 $\pm 20\%$ for normal diffusion and $\pm 30\%$ 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, $\sigma$, 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 ($\sim 0.6$ kpc for super-novae, see section 2.1) 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 $\sigma$ 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 equations 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 $\sigma$ 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 (eg 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 $\sigma = 1$ 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 further estimate of the scale height at the Galactic radius of the Solar System comes from radio astronomy (Erlykin and Wolfendale 2003). Here, Beck (2009) gives $\sigma = 1.7$ kpc, assuming that there is equipartition in energy between GCR and magnetic fields and a spatially constant GCR proton to electron ratio.

We conclude that, at the Galactic radius of the Solar System, values of $\sigma$ outside the range 1 to 2 kpc are unlikely.

2.3 Implied deficits from Gamma Ray Astronomy

2.3.1 Principle of the method.

High energy gamma rays are mainly produced by the interactions of primary GCR with the gas in the interstellar medium. Most gamma rays of energy above 0.3 GeV are produced by GCR primaries of energies of order several GeV. Specifically, Fatthoohi et al.(1995) quote mean proton energies of 2.6, 9.0, 40 and 200 GeV to produce gamma rays of mean energy 0.3, 1.0, 3.0 and 10.0 GeV, respectively. Thus, gamma rays of energy above 1 GeV come mainly from protons of energy above 9 GeV (average $\sim 20$ GeV), i.e. the energies responsible for much of the ionization in the Earth’s atmosphere. Since the inter-stellar medium is transparent to gamma rays of this energy their intensity depends on the primary GCR intensity. The gas column densities are known with reasonable accuracy and the gamma ray intensity along a line of sight after correction for the gas densities then gives an estimate of the primary GCR intensity.
Inspection of maps of the Galaxy, eg as given by Gies and Helsel (2005) and by Vallée (2005), shows that certain lines drawn from the Sun at particular longitudes pass largely through IA regions. The two most suitable longitudes are 60° and 270°. At these longitudes there is good SA, IA contrast. The measured gamma ray intensities in these directions will be compared with those in directions pointing towards the nearby SA to estimate the deficits.

2.3.2 Results from COS B measurements.

The search for SA, IA differences is not a new one. The COS B satellite (Bignami 1975, Bennett et al., 1976) gave early relevant gamma ray measurements and it is appropriate to mention the work here.

We (Rogers et al., 1988) and Bloemen et al., (1989) presented evidence for the spectral shape of GCR depending on Galactic latitude and SA, IA intensity differences. Our own work gave a difference of spectral exponent between SA and IA of 0.4±0.2 for the Orion Arm and its neighbouring IA. Thus an increasing deficit with increasing gamma ray energy was indicated. An analysis of the IA, SA contrast in CR intensity was also given by Van der Walt and Wolfendale (1988). These workers found values for the deficit in the range 10 to 35% for gamma rays of relevance to the work described here.

It should be remarked, however, that these results can only be regarded as indicative of an IA, SA spectral difference for two reasons:-

a) The latitude range is too high for our present purpose; Rogers et al (1988) use a mean latitude of 10° (compared with 0° in the next section) and here the inverse Compton contribution will also cause difficulties.

b) The later data from EGRET (section 2.3.3) are more accurate.

2.3.3 Results from EGRET measurements.

The EGRET data have been analysed by Hunter et al., (1997) who gave useful longitudinal distributions of gamma ray intensities for a range of gamma ray energies and latitudes. These include measurements in the Galactic Plane with -2 deg < b < 2 deg, where b is the Galactic latitude. Their distributions of gamma ray intensity as a function of Galactic longitude in this plane are used here to estimate the deficits.

To achieve this we take the difference in gamma ray intensity in the Galactic Plane at a longitude pointing towards a region dominated by an IA from a region pointing to a nearby SA. For the 60° IA region comparison is made with the region centred on 45° and the 270° IA region is compared with the 285° direction, the 45° and 285° regions each pointing towards the Sagittarius-Carina (S-C) Galactic Arm.

Table 2 gives the deficits estimated from the EGRET data for the two highest energy bands: 0.3 to 1 GeV and > 1 GeV. The deficits are estimated by taking the difference of the EGRET intensities divided by the column densities of gas (from Burton (1976) and Levine et al., (2006)). A correction has been applied for the fact that at each longitude there is a contribution from both
SA and IA regions (method a). A second method (method b) uses the fit given in Hunter et al (1997). In this fit it was found that over much of the relevant Galaxy a model in which there was a correlation of GCR intensity with total gas density (with a spatial smoothing) gave a good fit. Thus the fitted gamma ray intensity profile is used to estimate the deficits by subtracting the fitted intensities in each direction.

**Table 2.**

Spiral Inter-Arm Directions from the Sun.

| $L^\circ$ | Adjacent Arms | $d$ (kpc) | $\delta$ (%) (0.3-1 GeV) | $\delta$ (%) (> 1 GeV) |
|-------|---------------|--------|-----------------|-----------------|
| 60    | Local, S-C and Perseus | 2.7    | 25(18)          | 20(18)          |
| 270   | S-C and Perseus    | 3.0    | 29(26)          | 25(30)          |

It should be noted that the structures expected as the longitude changes from an IA to an SA direction are not convincingly present in the EGRET data. The data show a smooth downward trend from the Galactic Centre together with diffuse structures left over from point sources from which the direct radiation has been removed. Hence the majority of the deficit shown in Table 2 is due to the smooth decrease of intensity with longitude away from the Galactic Centre. The deficits shown in Table 2 are from the values read off the data as if the expected structures were present. Hence these values are upper limits on the deficits.

That the results are ‘reasonable’ can be seen by examining the plot from Hunter et al. (1997) of the ‘CR enhancement factor’ along the near-circular track of the Solar System along its path round the Galaxy. Only two regions of excess were found and these gave an effective deficit of 30%. However, these regions of excess do not correlate well with the known location of the Spiral Arms (Gies and Helsel 2005, Vallée 2005).

**2.3.4 Results from FERMI-LAT measurements.**

The most recent gamma ray results come from the FERMI-LAT observatory (Mizuno et al., 2011). These workers have examined the local region of the Outer Galaxy: specifically the Local Arm and the Perseus Arm regions as well as the IA region between the two. For gamma ray energies of greater than 0.3 GeV they found similar intensities from the Perseus arm and the IA region, implying a deficit of around zero. They found 15% less emission from the IA region than that in the Local Arm, implying a deficit of 15%. Hence, these values indicate deficits due to IA, SA differences of less than or order 15%.
2.3.5 Other Galaxies

Observations of the structure of our Galaxy from a position within it (i.e. the Earth) are difficult and, in principle, recourse can be made to other galaxies. Some galaxies, viewed end-on, have impressive haloes but the measurements yield information about electrons, and magnetic fields and electrons, of course, suffer extra energy losses so that their scale heights will be smaller than those for protons.

Of greater interest is the recent measurements of the Large Magellanic Cloud (LMC) by Abdo et al. (2010) using Fermi-LAT. These workers found what appeared to be a scale height of 0.2 kpc for cosmic rays responsible for gamma rays in the 0.2-20 GeV energy range. The primary cosmic rays are plausibly (authors’ term) the origin of the gamma rays by way of interactions with the inter-stellar medium and the radiation fields. This implies both cosmic ray protons and electrons. Such a small scale height, if applied to our own Galaxy, would imply a very large deficit according to equations 1 and 2 with almost zero GCR intensity when the Solar System is outside the SA. We examine this possibility.

Firstly, the phenomenon is restricted to the environs of 30 Doradus, the well known, ultra-active star forming region. Now many of the properties of the LMC are very different from those in the Galaxy (see Chi and Wolfendale, 1993) and, as these workers showed, the ambient cosmic ray flux is down by a factor 5-10 compared with the local flux. The recent Fermi-LAT measurements have refined this to a factor ∼2-4. Most importantly, Abdo et al (2010) found that the gamma ray emission from the LMC shows little correlation with the gas density. Concerning 30 Doradus, it is likely that strong stellar winds play a role in driving cosmic rays out of this small galaxy.

That there is nothing equivalent in our Galaxy comes from comparing the Galactic longitude distribution of gamma rays with that of molecular hydrogen - which is an indicator of cosmic ray production. Strongly active Galactic regions such as those associated with the Cygnus complex do not show the 30 Doradus phenomenon.

We consider that the information about the scale heights from other galaxies is not useful.

2.4 Discussion of the GCR Arm, Inter-Arm intensities.

The model adopted (see Table 1) gave predicted values of δ in the range 0 to 36% for σ from 1 to 2 kpc and for Arm separations of 2 to 3 kpc. The values are, necessarily approximate, for a number of reasons as well as the inaccurately known parameters:

a. Problems with likely differences in diffusion coefficients in the Arm and Inter-Arm regions.

b. Stochastic differences due to the actual distribution of relevant SN (and SN remnants) as distinct from their average values.

c. Possible effects of Galactic Winds.

Turning to the experimental observations, the derivation of the values of δ is necessarily imprecise. Foreground contributions are not easy to estimate. Nevertheless, a comparison of ‘observed’ and ‘expected’ is made.
Taking the data in Table 2 at face value and averaging we obtain an observed $\delta = 23 \pm 5 \%$.
Using the model, with $\sigma = 1$ kpc and the mean value of $d$ we predict $\delta = 25 \pm 10 \%$. There is thus reasonable agreement between the model and the data. Note that the model will give a much lower value of the deficit if the GCR scale height is closer to the value of 1.8 kpc from the fit to the EGRET data. This is not incompatible with the data in Table 2 which should be looked on as an upper limit rather than a measurement.

We conclude that the deficit in Inter-Arm versus Arm intensities over the Galactic circuit of the Solar System is most unlikely to have exceeded 30\% at cosmic ray energies of several GeV, the energy producing the majority of the ionization in the Earth’s atmosphere.

3 Influence of changes in the IA/SA GCR intensity on the climate

We have shown above that the changes in the GCR intensity as the Solar System moves from the IA to the SA of our Galaxy are of the order of 20\%. These match roughly the changes in the intensity observed during the 20th century due to centennial effects and due to the 11 year solar modulation. It has been shown that changes at this level cause at most a 0.07\degree C change in the present day mean global temperature (Erlykin et al., 2009b). Therefore, the changes in global temperature due to changes in the GCR intensity as we move from the IA to the SA are likely to be of the same magnitude. We conclude therefore that such changes cannot produce the large changes at the Ice Age epochs of the past $10^9$ years as postulated by Shaviv and Veizer (2008).

4 Cosmic Ray changes due to vertical oscillations of the Solar Cycle and species extinctions.

Just as the Solar System passes through successive SA, so it oscillates about the Galactic Plane. The period is about 64 Ma (Gies and Helsel, 2005) and the amplitude is $\sim 70$ pc (Thaddeus and Chanan, 1985). Interestingly, there is a cycle of ’fossil diversity’ with a period of $62 \pm 3$ Ma (Rohde and Muller, 2005 and Melott and Bambach, 2011). Connecting the two observations, Medvedev and Melott (2007) have proposed that the changes in the GCR intensity due to these oscillations was responsible for the extinctions which produced the fossil diversity. Hence, again, there is a model to be tested.

An immediate problem for the model is that with any reasonable GCR scale height (say 1 kpc, or above) the fall in GCR intensity at the extremes of the (vertical) oscillations will be negligible. As implied by section 2.2.2, a scale height of the necessary 100 pc is not possible. Therefore, the changes in the GCR intensity due to such vertical oscillations will be too small to produce species extinctions. Hence it seems most unlikely that they will produce the fossil diversity as postulated by Medvedev and Melott (2007).

A further point is that there will be two Galactic Plane crossings per cycle and thus an expected fossil diversity period of 32 Ma rather than 64 Ma. Medvedev and Melott (2007),
endeavour to circumvent this problem by assuming an anisotropy in the GCR intensity due to extragalactic effects. However, such effects appear unlikely in view of a near-symmetry in Galactic latitude of the non-thermal radio signal (Broadbent et al., 1989).

5 Conclusions

The Shaviv model of the difference in GCR rate in the IA and SA regions of the Galaxy gives large values for the change in the cosmic ray intensity in passing from the Spiral Arm of the Galaxy to the Inter-Arm region. The calculations presented here, using conventional values for GCR diffusion properties, give such changes at the level of 10 to 20% rather than the factor $\sim 3$ expected from his model. The data from gamma ray astronomy are compatible with the smaller changes presented here and are incompatible with the large changes proposed in Shaviv’s model. Furthermore, Wieler et al. (2011) showed from meteorite data that in the last 10 Ma the GCR intensity has not varied by more than 10%. Now, some 10 Ma ago the Solar System was well into the IA region compared to its position in the Local Arm now so that the probability of the local SA, IA deficit being as high as or greater than 20% must be small.

It has already been shown by Overholt et al (2009) that the peaks and troughs in the Shaviv distribution do not correspond to crossings of the SA in the Galaxy. Here we show that the estimated intensity variations from the Shaviv distribution are also unrealistic, if we use conventional assumptions of the GCR parameters.

We conclude therefore that the use of this model to claim that there is palaeontological evidence for a connection between cosmic rays and the climate is unjustified, unless some of the conventional assumptions of GCR parameters are wrong. Added to our earlier analysis of the near contemporary GCR and Global temperature measurements (Erlykin et al 2009a and 2009b) which showed no evidence for a GCR-climate link we conclude that there is no hard evidence for such a link.

An explanation of the reason for the initiation of the Ice Age epochs of the past $10^9$ years remains to be found. Such initiation may possibly have an astronomical cause by way of the effect of GCR of PeV energies on the electrical conditions of the atmosphere. The periods of increase here are of order 20 ka occurring every Ma or so. The 20 ka period arises from the rapid diffusion of the PeV particles which are deemed responsible. The fact referred to by Erlykin and Wolfendale (2001) is that proximity to Supernova remnants in the Solar System’s passage through the Galaxy causes increases by several orders of magnitude in the intensity of terrestrial GCRs at PeV energies (as distinct from a few percent in the GeV energy range). This might have relevance, the multiplying factor coming by way of effects on the electrical conditions of the atmosphere.

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