Long term time variability of cosmic rays and possible relevance to the development of life on Earth

A.D. Erlykin 1,1a and A. W. Wolfendale 1
(1) Department of Physics, Durham University, Durham, UK
(1a) Permanent address: P N Lebedev Institute, Moscow, Russia

February 27, 2010

Abstract

An analysis is made of the manner in which the cosmic ray intensity at Earth has varied over its existence and its possible relevance to both the origin and the evolution of life.

Much of the analysis relates to the 'high energy' cosmic rays ($E > 10^{14}$eV; $= 0.1$PeV) and their variability due to the changing proximity of the solar system to supernova remnants which are generally believed to be responsible for most cosmic rays up to PeV energies. It is pointed out that, on a statistical basis, there will have been considerable variations in the likely 100 My between the Earth's biosphere reaching reasonable stability and the onset of very elementary life. Interestingly, there is the increasingly strong possibility that PeV cosmic rays are responsible for the initiation of terrestrial lightning strokes and the possibility arises of considerable increases in the frequency of lightnings and thereby the formation of some of the complex molecules which are the 'building blocks of life'.

Attention is also given to the well known generation of the oxides of nitrogen by lightning strokes which are poisonous to animal life but helpful to plant growth; here, too, the violent swings of cosmic ray intensities may have had relevance to evolutionary changes.

A particular variant of the cosmic ray acceleration model, put forward by us, predicts an increase in lightning rate in the past and this has been sought in Korean historical records.

Finally, the time dependence of the overall cosmic ray intensity, which manifests itself mainly at sub-10 GeV energies, has been examined. The relevance of cosmic rays to the 'global electrical circuit' points to the importance of this concept.

Key words: cosmic rays, lightning, evolution

1Corresponding author: Erlykin A.D., e-mail address: erlykin@sci.lebedev.ru, telephone: +7-499-135-87-37, fax: +7-499-135-78-80
1 Introduction

1.1 The cosmic radiation and its relation to climate

Over the 4.5By since the formation of the Earth the astronomical environment has been variable and, with it, the cosmic ray (CR) spectrum (this is in addition to solar irradiation changes caused by the varying Sun-Earth distance and Earth obliquity— the 'Milankovich effect'). There are three main sources of CR variability: the Geomagnetic field, the Sun (by way of the solar wind and the occasional 'solar cosmic rays' associated with solar flares) and the presence of nearby CR sources. The first two relate to variations of the low energy particles, principally below 10 GeV, and the last-mentioned to all energies, with increasing variability as the energy increases, the highest energy recorded being $\sim 10^{20}$eV (ie $10^{11}$GeV).

Further remarks on 'cosmic rays' are necessary. Under 'normal circumstances' (quiescent Sun) the CR, composed mainly of hydrogen, helium and heavier nuclei, have a power law spectrum from about 1000 GeV to 3 PeV. At energies above 3 PeV the spectrum steepens. Below 1000 GeV there is a progressive 'flattening' of the spectrum (as one proceeds towards lower energies) due to both the Geomagnetic field and the solar wind. The magnitude of the flattening depends on the 11 year cycle of the solar wind and is a function of geographic latitude and energy; it is very small above 100 GeV.

The energy content of Galactic cosmic rays (GCR) is an important parameter. The energy densities at earth above the energies indicated are, in units of $Jm^{-3}$, $\sim 0.05(>10^8eV)$, $\sim 0.03(>10^{10}eV)$, $3\times10^{-3}(>10^{12}eV)$, $10^{-4}(>10^{14}eV)$ and $10^{-6}(>10^{16}eV)$ (Wolfendale, 1973). By contrast, the total solar irradiance is some $10^8$ times greater than that for all CR.

In addition to an interest in its own right, the variation of the GCR energy spectrum with time has relevance to atmospheric properties and thus (perhaps) to 'life' on Earth. The first mention of a possible effect of CR on climate seems to be that of Ney (1959), the claimed mechanism being by way of the effect of CR ions on aerosols, leading to enhanced cloud formation. A number of workers have, more recently, followed up the suggestion (eg Svensmark and Friis-Christensen, 1997; Palle Bago and Butler, 2000; Marsh and Svensmark, 2000; Svensmark, 2007). Indeed, Svensmark (2007) has even coined a term for the new discipline: 'Cosmoclimatology'!

Although, a priori, it might be thought that such a mechanism was unlikely, based on the $10^8$ factor referred to above, Voiculescu et al. (2006) have claimed that there is a GCR, low cloud cover correlation over restricted regions of the Globe. Harrison and Ambaum (2008) have claimed that 'the mechanism' exists on the edges of clouds by way of a large reduction in the critical supersaturation needed because of a large degree of droplet charging.

This is where it must be pointed out that direct CR may affect the climate. The effect of GCR on the 'Global electrical circuit' (Williams, 2002; Rycroft et al., 2008) has been studied by Tinsley (2008) and Aplin et al. (2008) who consider the effect of 'electro-freezing' and 'electro-scavenging'; these processes
lead to changes in the density of cloud condensation nuclei. In all these processes it is important to know the manner in which CR ionization varies with atmospheric depth. Such studies have been made by Usoskin and Kovaltsov (2006) and Velinov et al. (2009).

Despite doubts about the appreciable effect of GCR on clouds in the lower troposphere, (Sloan and Wolfendale, 2008; Erlykin et al., 2009b), in the stratosphere, where GCR intensities are higher and there are the occasional ‘solar protons’, there are strong signals. That there is an 11-year cycle in the ozone density is beyond doubt, and Lu (2009) has presented strong evidence for a strong causal correlation between GCR and polar ozone loss over Antarctica (the ‘ozone hole’). The identification of GCR as being responsible, as distinct from solar irradiance, comes from CR being the only source of low energy electrons at the depth in question and the ozone hole being in the Geomagnetic Pole region where the CR intensity is a maximum. Other related effects include the effect of strong Geomagnetic storms and Forbush decreases of GCR intensity on the total ozone content and the lower atmosphere (troposphere and lower stratosphere) (Lastovicka and Krizan, 2005). It must be mentioned, however, that the claimed effect of Forbush CR decreases on the liquid cloud fraction in the troposphere (and other atmospheric parameters) by Svensmark et al. (2009) was not confirmed by Laken et al. (2009).

A less certain, but potentially important, process, is that suggested by Shumilov et al. (1996). These workers were impressed by the increase in aerosol concentration after solar proton events (particularly the ‘Ground Level Event’ of 16/02/1984. The increase occurred at the altitude range, ~17km, where energetic solar protons lose their energy in the atmosphere). The mechanism put forward was CR ionization, as a source of ion nucleation, stratospheric sulphate aerosols forming on the condensation nuclei (Arnold, 1982; Hofman and Rosen, 1983).

The importance of solar particle events in polar regions has been pointed out by Usoskin et al. (2009). A related argument, which may have relevance to the claimed low cloud cover, GCR correlation, is due to Kudryavtsev and Jungner (2005). These workers argue that the extra CR induced aerosols cause atmospheric transparency changes which in turn affect tropospheric climate. They quote other workers (e.g. Starkov and Roldugin, 1994 and Pudovkin et al., 1997) as having also observed transparency decreases during solar proton events.

1.2 Extensive Air Showers

Our work reported here relates mainly to much higher energies than those concerned with solar effects (which are mainly below some 10s of GeV), specifically 0.1PeV and above; these particles being manifest by their production of extensive air showers (EAS). Some remarks about EAS are necessary. When a particle (often a proton) of ‘high energy’, say above 0.1PeV, is incident on the atmosphere it interacts with the air nuclei to produce a cascade of secondary particles (mainly pions of the three charge states: positive, negative and zero).
The (unstable) charged pions decay into muons ('heavy electrons'), which in turn may decay into electrons, and the neutral pions decay into gamma rays. The process is repeated by the primary proton which survives the interaction with reduced energy and those energetic pions which interact further before they have had chance to decay.

The effect of the interactions is to build up an 'electromagnetic cascade' of electrons and gamma rays. To be quantitative, a 1PeV primary will generate a shower having maximum number of charged particles (mainly electrons) at an atmospheric depth of \( \sim 560\text{mb} \), ie height in the atmosphere of \( \sim 5\text{km} \). The mean number of particles at 'shower maximum' would be \( \sim 5.3 \cdot 10^5 \) and the number of particles at ground level for a vertically incident proton would be \( \sim 1.4 \cdot 10^5 \) (Ambrosio et al., 1997).

The important feature of EAS relevant to the initiation of lightning strokes is the high density of secondary electrons near the axis of the shower. Recent calculation by us (Erlykin et al., 2009a) for 100PeV protons and a height of 2km give a particle density at 1m from the shower axis of \( \sim 2 \cdot 10^5 \text{m}^{-2} \). For a primary of energy 1PeV the density will be \( \sim 2 \cdot 10^3 \text{m}^{-2} \), still a very high value. On the axis itself, the particle density will be some ten times greater.

1.3 Relevance of EAS to the origin of life

The possible relevance to the atmosphere (and 'life', including humans), is by way of the very likely role of EAS particles in the initiation of lightning (eg Gurevich and Zybin, 2001, Chubenko et al., 2009, Gurevich et al., 2009 and Chilingarion et al., 2009). The idea is that the leader lightning stroke is initiated by runaway electrons which are generated by particles in EAS. The references quoted include observed coincidences between EAS and lightning and not just the undoubted effect of thunderstorm electric fields on the energies of CR particles (which are, themselves, not necessarily members of EAS). The whole question of the electrical conditions of the atmosphere, including its most dramatic manifestation (lightning), is tied up with CR insofar as they represent an important source of ions near ground level and the major source at altitudes above a few km. Tinsley et al., (2007), Rycroft et al., (2008), and others have pointed out the great importance of the 'global electric circuit' - to which CR contribute considerably - even when the changes considered have been small. The global electric circuit possibly can be influenced also by gigantic red sprites and blue jets. Presumably they are initiated by electrons, which are created by CR and accelerated in their upward movement to runaway energies by thunderstorm electric fields (Yukhimuk et al., 1998; Tonev and Velinov, 2003). Effects consequent upon very large changes in CR intensity at Earth could be profound. The question of the global electrical circuit is considered in more detail later.

Lightning has, conceivably, played a role in the evolution of life. Starting with pre-life, the work of Miller and Urey (Miller, 1953) involving the passage of electrical discharges through a 'pre-biotic soup' of appropriate chemicals (water, methane, ammonia, etc) caused quite complex molecules to be generated:
amino acids, monomers, RNA etc, which were necessary pre-cursors of elementary life. Lightning could, conceivably, have provided the required discharges. It must be remarked that there are different views about the origin of life; some argue that the initial complex molecules arrived by way of comets instead (eg Hoyle and Wickrama-singhe, 1993). Here, we persist with the Miller and Urey hypothesis (MU) since very recent work (eg Parman, 2009) concludes that there was little free oxygen in the atmosphere prior to 2.45 Gy BP (ie 2.45×10^9 years before present) and the MU hypothesis would have a chance of success. The necessary water oceans were probably present by 4.2 Gy BP (‘Bada, 2003; Parman, 2009).

Later, when ‘life’ was advanced, lightning would have had an effect on evolution by virtue of the obnoxious NO_x (‘NO and NO_2) produced. Even now, some 20% of NO_x comes from lightning - much higher lightning rates would have been important. NO_x effects include modifications to atmospheric chemistry, with particular relevance to ozone levels and effects on hydroxyl (OH) radicals - thereby increasing the concentration of greenhouse gases.

There is a wealth of literature on NO_x production by lightning (eg Betz et al., 2008). Allen et al. (2009) estimate that the rate of production of NO_x from lightning is \( \sim 10^{13} \text{kg} \cdot \text{year}^{-1} \), to be compared with the total atmospheric mass of \( 5 \cdot 10^{18} \text{kg} \) and a mass of ozone of order \( 5 \cdot 10^{11} \text{kg} \) (Allen, 1973).

Although NO_x is damaging to mammals, plants benefit from the nitrates coming from NO_x reactions. The interplay between the development of plants and of mammals means that periods of low CR intensity (low NO_x) as well as those of high intensity are important. The likelihood of CR effects here is, no doubt, less contentious and should be put alongside the various meteorological factors, such as temperature and rainfall, which have affected the evolution of life.

Even if none of the above effects turn out to be important, a knowledge of the past history of the intensity of high energy GCR (HECR), by which we mean 10^{14} \text{eV} and above, is of considerable interest because of its relevance to the (still unsolved) problem of the origin sites, acceleration mode and propagation characteristics of the primary particles.

1.4 Scope of the paper

We start with an analysis of the time variation on a statistical basis using results provided by us earlier (Erlykin and Wolfendale, 2001a), and based on our supernova remnant (SNR) model of GCR acceleration (Erlykin and Wolfendale, 2001b). Later we examine the recent past - some 30,000 y - assuming that our Single Source Model of the ‘knee’ in the spectrum at \( \sim 3 \text{PeV} \) (Erlykin and Wolfendale, 1997, 2003) is correct. In this model, which is now being increasingly accepted (eg Hu, 2009), we argue that the extreme sharpness of the transition region of the energy spectrum is indicative of the presence of a recent, nearby SNR.

Finally, some remarks will be made about the possibility of the total intensity of CR, as distinct from just the high energy component, having relevance to the
terrestrial climate and thereby to evolutionary mechanisms. This is left to last because we are less convinced by the claims for its relevance to the lightning hypothesis but it is included for its relevance to the other mechanisms.

2 Variations of Galactic cosmic rays over the past million years using the results of Erlykin and Wolfendale (2001a)

2.1 Time profiles as a function of energy

It is assumed at this stage that the Geomagnetic field is constant and that the solar wind modulation is ‘normal’, viz giving only an 11-year variation in total CR intensity with peak-to-peak magnitude of, typically, 10%. Small, long term variations of solar irradiance are ignored. The CR variations are thus due to the changes in the Galactic component.

Figure 1 shows a typical time-profile of the GCR intensity for different energies from our supernova model for CR production, Erlykin and Wolfendale (2001a, b). Protons are assumed in the calculations but the results can be applied to other nuclei by simple rigidity-transformation (rigidity= $E/Z$, $E$ and $Z$ being particle energy and charge respectively). It will be noted that, in addition to the rare upward excursions, which are particularly marked at the highest energy (taken here as 10 PeV, ie $10^{16}$eV), there are long periods - by chance - when the average level is well below the long term average value. The physics behind the intensity behaviour shown in Figure 1 is straightforward and will be described. It is well known that the diffusion coefficient of GCR varies with energy, increasing as the energy increases. Thus, the ‘wave’ of GCR from a source (SNR in this case) propagates more rapidly, and with a narrower time width, at high energy. This is apparent in the Figure, where the high energy ‘spikes’ are higher and narrower than the low energy ones. It should be added that although we have taken the sources as being SNR - the most likely situation - a similar type of source, such as a pulsar, would give a similar result.

The frequency of excursions in CR intensity can be examined as follows. Starting with the positive excursions, we define ‘peaks’ above nearby minima and give a logN,logS plot, where $S$ is the intensity of a peak and $N$ is the number of times such a peak intensity, or bigger, is achieved. The result is shown in Figure 2.

We remember that the data are binned in 1000y (ie they represent the average intensity over such periods). The lines drawn in Figure 2 are simple parabolic ‘best-fits’. An indication that the calculations are correct comes from an examination of the slopes of the tangent in Figure 2, ie the $\gamma$-values, where $N(> S) \propto S^{-\gamma}$, ie $logN(> S) = -\gamma logS + constant$. In the ‘middle region’, say $logS = 1$ or 2, the shape should follow a line of slope 1 since, here, we are dealing with, essentially, a two-dimensional distribution of sources (SNR), these being mainly further away than the half-thickness of the SNR distribution.
about the Galactic Plane (half width at half maximum ≃ 250 pc). The reason is straightforward: a source at distance $x$ will give $S(x) \propto 1/x^2$ so that sources within $x$, of number $\propto x^2$, will have intensity $> S$, thus $N(> S) \propto x^2 \propto 1/S$; $\gamma = 1$. At $S$ values below 1 the curvature arises from the loss of small $S$-values due to 'source-confusion'. Eventually, above $\log S = 2$, the slope should tend to -1.5 because some of the sources will be nearer than 250pc and the distribution of relevant sources tends to isotropy (the argument is similar to that for 1-D with the number of sources within distance $x$ being $\propto x^3$).

Of particular interest is the extension to cover a period of 100My, the likely 'window' when other conditions on Earth were suitable for elementary life to form. Presumably (but not definitely) this was immediately after the 'late heavy bombardment' some 3.9Gy before present (Parman, 2009). It can be remarked that the earliest fossils date from about 3.5Gy before present. We note than in 100My of order one peak would occur for energy above 10PeV with intensity some 3000 times the datum. Taking the median value of $\log I = 1.69$, the enhancement is a factor of about 60. Such an enhanced intensity would continue for a few thousand years.

### 2.2 Temporal effects

It is of relevance to examine the fraction of time for which the CR intensity would be above and below certain limits, over our 'standard' period of 1My. This is given in Figure 3 for particle of energy 10PeV. It will be noted that for 10% of the time the intensity will be more than ten times the median and for 10% of the time, the intensity would be less than one quarter of the median.

### 2.3 Short-term variations for 10,000 year bins

Figure 4 shows the equivalent to Figure 1 for time bins which are ten times that used previously, viz now 10,000 years. The 10PeV peaks are typically 5 times smaller than in Figure 1. The equivalent of Figure 2 would give an enhancement by about a factor of at least 10, lasting 10,000y every 100My.

### 3 The likely high energy GCR intensity in the immediate past

In earlier work (Erlykin and Wolfendale, 2003), we identified the 'single source', responsible for the 'knee' in the cosmic ray spectrum as probably being a supernova in the distance range 250 - 400 pc from the Earth and being of age in the range 85 to 115 ky ($1\text{pc} = 3 \cdot 10^{16}\text{m}$). Figure 5 shows the results of our calculations for a distance of 300pc and the range of ages just indicated. It will be noted that the ratio of the predicted intensity (for 10PeV) at the peak to that at present covers a wide range: from 10 to 1000. Certainly, in the 'recent past' (some thousands to tens of thousands of years), the intensity of high energy GCR should have been significantly higher than at present.
Studies have been made using radioactive nuclei in ice cores of different ages of past CR intensities but these refer to low energy particles. At this stage of the present work, with the emphasis on high energy particles (≃ PeV), we have examined historical records over the past centuries of both lightning frequency and other, relevant, atmospheric phenomena. Classical literature is replete with mention of lightning and other dramatic atmospheric phenomena. Zeus was the Athenian God of lightning and, for example, Chaak was the Mayan Lightning God (Looper, 2003), the period of relevance being the 8th Century AD. However, apart from one source of information, the records cannot be used to give lightning rates (Stephenson, private communication, 2009). The exception relates to data from Eastern chronicles, which date from about 1400, specifically, the annals of the Chosun-Dynasty relating to the Korean Peninsula are comprehensive and have been analysed by Lim and Shim (2002); these authors remark that the ‘time variation of the (climate) indices shows a good agreement with a similar analysis done for China by other authors’. There appears to be nothing of significance for other areas of the Globe (Stephenson, 2009, private communication).

Returning to the Korean records, Lim and Shim (2002) have given such information for the period 1400 - 1900 and this shows interesting variability. It is true that the average rate of lightning per century was higher in the past but the variability was so dramatic as to make any quantitative estimate of the likely CR-induced variation suspect. For example, with respect to the ‘final’ period, 1800 - 1870, where the mean rate was given as about 1 stroke per year, the mean values for the factors of increase were as follows:

- 1400 - 1500: 3 (3)
- 1500 - 1600: 7 (5) (with occasional yearly frequencies above 20 strokes per year)
- 1600 - 1700: 4 (2)
- 1700 - 1800: 5 (3)

No doubt, various meteorological factors unrelated to cosmic rays were responsible for at least some of the variability and we have endeavoured to take out some of this variability by dividing the lightning frequency by the annual occurrence of rain and snow from the same source of data. The ratios, again with respect to the 1800 to 1870 period, are shown in brackets. It will be noted that the two sets of figures are rather close.

Contemporary values of lightning frequency would allow a check on the possibility of a ‘time-gradient’ in lightning frequency but these are not available. Furthermore, there are difficulties in ensuring consistent criteria on what to include in the 470 year long record (Jongman Yang, 2009, private communication). Although the fact that China seems to have shared the variability leads us to believe that the mean lightning rate on a Global scale was probably somewhat higher than recently. It must be said, however, that there can be no question
(yet) of defining the distance and age of the single source, using this method. More extensive studies remain to be done.

4 Variation of the intensity of low energy cosmic rays

4.1 General Remarks

As remarked earlier (Section 1), low energy CR are modified in intensity by the Geomagnetic field and the solar wind as well as, to a lesser extent, by nearby SNR. To this should be added solar CR themselves. In all cases there may be relevance to the main thrust of the present work as will be demonstrated.

4.2 The Dwyer-model for lightning activity

Dwyer (2005) has claimed that non-uniformities in the atmospheric electric field can be amplified by the ‘steady background of atmospheric cosmic rays’ and thus influence lightning activity. Satori et al.(2007) have, indeed, found evidence for annual and semiannual areal variations of Global lightning on an 11-year cycle although we, ourselves, have failed to find the expected CR - correlated variation of lightning frequencies over the geographical land masses. It must be said, however, that these have been reports, by Stozhkov (2003), for an increase in the GCR intensity leading to a growth of thunderclouds.

What is clear is that the CR intensity (Galactic or Solar) will have an effect on the Global electric circuit, as already mentioned in connection with the effect on the charging of condensation nuclei. The effect will be on both the ‘fair weather field’, by virtue of CR ionization (Kniveton et al., 2008), on the field in clouds through the changes to clouds referred to already and to the ‘current generators’ in thunderclouds (Tinsley et al., 2007) if the Dwyer model is, indeed, applicable.

If there is indeed a dependence of lightning frequency on the total CR intensity, as distinct from on high energy GCR intensity, then interest will focus on variations of the Geomagnetic field (reversals) and of the solar wind - both of which can be considerable. However, it should be noted that the effects here will be confined largely to high latitudes and the higher regions of the atmosphere where low energy CR are involved.

4.3 The role of magnetic field reversals

The field reversal, as such, has no effect on the surface level CR intensity in the sub-100 GeV region, rather it is the period between reversals when the field is at a low level. A change in CR intensity by a factor less than about 3 would be expected. ‘Contemporary’ reversals number about 200 over the period of about 165My for which data are available (Creer and Pal, 1989). Such variations in CR rate are probably not of great importance from the evolutionary point of
view. Of greater relevance would be the (likely) dramatic changes in the Geomagnetic field during the early stages of the Earth’s formation, but these are of unknown magnitude. What can be said is that they would presumably lead to large reductions in the CR rate.

4.4 The solar wind

Modifications to the solar wind by intrinsic solar changes and changes to the interstellar medium in which the solar system is immersed will cause GCR changes. The former, which may give rise to solar flares, will be considered in the next section. Concerning the latter, Vahia (2006) has made a detailed study of the expected modification to the GCR spectrum at Earth as the solar system passed through various environments: spiral arm, interarm, a Giant Molecular cloud and the immediate vicinity. Over the last 10My the local interstellar medium density has varied from $0.08\text{cm}^{-3}$ in the 'Local Fluff' (Frisch, 1995), the weak local interstellar cloud which provides the pressure for the confining solar wind bubble and occupies about 5pc, through $4\text{cm}^{-3}$ for the Geminga SNR to $5 \times 10^{-4}\text{cm}^{-3}$ for the interarm region. The result is that above 100 GeV there is no change but at an energy of 3 GV, typical of the ‘total CR intensity’, the reductions in intensity cover a range of about 10. At 300MeV, an energy of relevance to particles entering in Polar regions, the range is even bigger and is about 100.

The times taken to cross some of the regions listed above cover the range 0.1 - 20My so that for such periods the CR intensity will have fallen by up to one or two orders of magnitude.

Concerning the spiral arm/interarm regions, mention should be made of the works of Shaviv (2002, 2003) and later publications. The argument related to the periodic crossings of spiral arms where the GCR intensity is higher than in the interarm regions. It was claimed that the ‘icehouse’ episodes, which numbered 4 in 500My, were due to the enhanced GCR intensity causing more low cloud and thus lower ground level temperatures. This argument has been elaborated upon by Svensmark (2007) in his ‘Cosmoclimatology’ works. However, there are problems. Firstly, our own work (unpublished) using cosmic gamma ray data from the EGRET instrument on the Gamma Ray Observatory (Hunter et al., 1997) shows that enhancement in the sub-10GeV region is less than a factor 2. This result is consistent with our earlier work (Rogers et al., 1988). Interestingly, there should be a bigger arm, interarm contrast in the PeV region because of the higher density of supernovae in the spiral arms but the rapid spatial diffusion of these particles reduces its magnitude. Secondly, Melott et al. (2009) have used recent CO data (which provides information about molecular hydrogen in the Galaxy and the densities of young stars) to make more robust estimates of the positions of the spiral arms and the times of transit of the solar system; these estimates cause the claimed correlations of arm transit and icehouse estimates to disappear. Melott et al. argue that ‘the correlations cannot be resurrected by any reasonable pattern speed’.
4.5 Solar Flares

Very large flares can, in principle, cause big changes to the low energy CR intensity. A number of workers have considered the topic of ‘cosmic rays and ancient catastrophes’. Wdowczyk and Wolfendale (1977) drew attention to the fact that the \( \log N, \log S \) curve for solar CR, where \( S \) is the ‘fluence’ (energy per unit area), is linear, at Earth, up to the strongest flare recorded in the period from 1956. The maximum value is \( 1 \text{Jm}^{-2} \), averaged over the Earth’s surface, and the corresponding rate is about \( 2 \cdot 10^{-2} \text{y}^{-1} \). The current ambient CR energy intensity is \( 1 \text{Wm}^{-2} \) to that, for a period of 10h (a typical flare length), the fluence is \( 4 \cdot 10^{-2} \text{Jm}^{-2} \). The strongest flare so far recorded therefore corresponds to a 25-fold increase in CR intensity (at the Earth’s surface) for this period of 10h. Extrapolation to the inevitable stronger flares with much lower frequency is impossible with any accuracy in view of lack of knowledge of the details of flare acceleration. However, extrapolation using an exponential fall beyond the maximum flare fluence seen so far would indicate a fluence of \( 10^5 \text{Jm}^{-2} \) every 100My on average. Such a fluence would correspond to a radiation level of \( \sim 10 \text{ Röntgen} \), a serious dose for mammals. The derived rate would not be inconsistent with the results of \(^{10}\text{Be} \) and \(^{26}\text{Al} \) studies in sea sediments.

4.6 Very local supernovae

Wdowczyk and Wolfendale (1977) and others have derived the fluences of CR at earth, for both particles and gamma rays, which would result from close proximity to a SN.

There will be a weak gamma ray flash, weak because of the absorption close to the source, the average fluence for a SN which has ‘unit probability’ of being seen in \( \sim 100\text{My} \) being \( \sim 10^4 \text{Jm}^{-2} \). Insofar as the ‘flash’ lasts for several hundred days the contribution would be small in comparison with the ambient CR intensity of \( \sim 1 \text{Wm}^{-2} \), ie \( \sim 10^5 \text{Jm}^{-2} \) over 100 days.

For particles, the changes in CR intensity are as given in the Figures, ie the spikes, which have magnitudes and time widths which are a function of particle energy.

4.7 Gamma Ray Bursts

Concluding this brief discussion of sub-10GeV CR and their possible effect on the Earth’s atmosphere and the Earth’s ‘inhabitants’, mention must be made of ‘gamma ray bursts’. Although most bursts are at cosmological distances it is possible that there has been one or more bursts from the Galactic Centre, the most recent having been \( \sim 12\text{My} \) ago (Sanders and Prendergast, 1974). Wdowczyk and Wolfendale (1977) have examined this possibility and derived a fluence of \( 1 \text{MJm}^{-2} \) at the top of the atmosphere. The corresponding radiological dose is \( \sim 100\text{R} \). Although it is true that the gamma rays, being in the MeV region, will be largely absorbed by the 20-30km altitude region their effect on
the ozone layer and the dynamics of the atmosphere (see Section 5) make an effect on the troposphere inevitable. There is much information about CR effects on lunar rock, principally from solar CR bursts, but there are, as yet, no definitive records of gamma ray bursts - indeed one could visualise determining the energy spectrum of CR from the cascade damage in the lunar regolith region if quantitative measurements were possible. It is hoped that this situation will be realised.

5 Discussion and Conclusions

The two energy ranges can be considered in turn: the PeV region, where the occasional excesses and deficits of GCR, are relevant, and the sub-10 GeV region where solar-induced phenomena are important.

In both cases we are concerned mainly with induced lightning, the PeV region relating to the Gurevich effect of EAS cores initiating lightning and the sub-10 GeV region relating to the claim by Dwyer and others that the overall-CR-induced ionization level is important for lightning generation.

In neither case is it evident that the lightning rate would be proportional to the CR intensity. Although detailed calculations for the Global electric circuit have been made (the 'EGATEC-model' of Odzimek et al., 2009) the functional form has not yet been derived (Odzimek, 2009, private communication). However, it is evident from the physics of the lightning process that many regions with thunderclouds which were not hosts to lightning would become so if the PeV GCR rate were to increase. A similar situation would be expected for the sub-10 GeV case.

Starting with the PeV region, the results are, from the GCR point of view, straightforward: considerable fluctuations in PeV GCR intensities should occur over long periods of time (My). At high energies, in fact, the variations would be bigger than quoted if, as seems possible, the diffusion coefficient in the 'local bubble' in the interstellar medium, in which we reside, were higher than the conventional one - for a uniform interstellar medium - adopted in our calculations.

It can be remarked that, since most of the fluctuations are stochastic and geometrical in origin, CR production by other types of 'discrete' sources, such as pulsars, would give rather similar results. The very close SNR responsible for the dramatic upward high energy CR intensity fluctuations are unlikely to have given dramatic 'gamma ray flashes' which could have had an effect on the Earth. A gamma ray burst at the centre of the Galaxy - for which there is no direct evidence - could have been 'serious', however.

Turning to the relevance of the results to lightning and to possible biological effects, in the 100My window for life creation, the considerable increase in 10PeV intensity for some tens of thousand years, with its presumed increased lightning rates - could have played a part in pre-biotic life generation.

At later stages, when life was evolving, the occasional lightning excesses with increased production of NO x could have had pronounced positive effects
on vegetation and negative effects on humans. However, evolutionary spurts for non-plant life may have occurred for those long periods when the 10PeV intensity was low. In this connection, because CR induced ionization is related to both effects NO\textsubscript{x} and lightning, the extension of recent models (Usoskin and Kovaltsov, 2006; Velinov et al., 2009) to higher energies will be of considerable interest.

The claimed PeV increase in the recent past could (‘over, say, 5000 years’) conceivably be found in historical records of changes in lightning rates more extended than those carried out by us so far.

Turning to the variations in the sub-10GeV intensity, if, indeed the lightning rate is affected by CR of all energies, then, again, CR-induced evolutionary effects are expected. These changes would be expected to be confined to high latitudes and high altitudes although still important if the claimed mechanisms of transmitting stratospheric changes to the troposphere (eg Haigh, 1996; Kudryavtsev and Jungner, 2005) are effective. The main causes envisaged relate to the movement of the solar system through different environments in the interstellar medium, geomagnetic field reversals and solar flares. Even without lightning, changes to the global electric circuit could have generated important climatic effects.

In conclusion, it is argued that CR should be considered alongside other astronomical factors, most notably changes in the Earth-Sun distance and the Earth’s spin axis (‘Milankovich effects’), in causing effects on the initiation and later evolution of life.

Acknowledgements

The Physics Department of Durham University is thanked for the provision of excellent facilities. Drs A Odzimek and K Aplin and Professor A Chilingarian are thanked for helpful comments. The authors are grateful to the Kohn Foundation for supporting this work and to Professors Jongman Yang and F.R. Stephenson for helpful advice.
References

1. Allen, C W, 'Astrophysical Quantities', Athlone Press (1973).

2. Allen, D, Pickering, K, Pinder, R and Pierce, T, 'Impact of lightning - NO emission on eastern United States photochemistry during the summer of 2004 as determined using the CMAS model', Proc. 2009 CMAS Meeting.

3. Ambrosio, M, Aramo, C, Colesanti, L, Erlykin, A D and Machavariani, S K, 'Frontier Objects in Astrophysics and Particle Physics', Eds. F. Giovannelli and G. Mannocchi, Italian Phys. Soc, 57 (1997), 437.

4. Aplin, K I, Harrison, R G and Rycroft, M J, 'Planetary Atmospheric Electricity', Eds. F.Leblanc et al. doi:10.1007/978-0-387-87664-1.

5. Arnold, F, 'Ion nucleation - a potential source for stratospheric aerosols', Nature, 299 (1982), 134.

6. Bada, J,L, ‘Origins of Life’, Oceanography, 16, (2003), 3, 98.

7. Betz, H D, Schumann, U and Larocque, P, (eds) 'Lightning, Principles, Instruments and Applications', (2008), Springer.

8. Chilingarian, A, Daryan, A, Arakelyan, K, Reymers, A, Melkumyan, L, 'Thunderstorm correlated enhancements of Cosmic Ray Fluxes detected on Mt. Aragats', Proceedings of international conference FORGES 2008, Nor Amberd, Armenia, pp./ 121-126, TIGRAN METS, 2009.

9. Creer, K M and Pal, P C, 'On the frequency of reversals of the Geomagnetic Dipole', Catastrophes and Evolution -Astronomical Foundations, ed. Clube, SVM, Cambridge University Press, (1989), 113.

10. Chubenko, A P, Karashtin, A N, Ryabov, V A, Shepetov, A L, Antonova, V P, Kryukov, S V, Mitko, G G, Naunov, A S, Pavljuchenko, L V, Ptitsyn, M O, Shalamova, S Ya, Shlyugaev, Yu V, Vildanova, L I, Zybin, K P and Gurevich, A V, ‘Energy Spectrum of lightning gamma emission’, Phys. Lett. A. (2009) doi:10.1016/j.physleta.2009.06.031.

11. Dwyer, J R, 'The initiation of lightning by runaway air breakdown', Geophys. Res.Lett., 32, (2005) L20808.

12. Erlykin, A D and Wolfendale, A W, ‘A single source of cosmic rays in the range 10^{15} - 10^{19} eV’, J.Phys.G. 23, (1997) 979.

13. Erlykin, A D and Wolfendale, A W, ‘Supernova remnants and the origin of the cosmic radiation : I SNR acceleration models and their predictions’, J.Phys.G., 27, (2001b) 941.

14. Erlykin, A D and Wolfendale, A W, ‘Supernova remnants and the origin of the cosmic radiation : II spectral variations in space and time’, J.Phys.G. 27, (2001a) 959.
15. Erlykin, A D and Wolfendale, A W, ‘High-energy cosmic gamma rays from the ‘single-source’, J.Phys.G. 29, (2003) 709.

16. Erlykin, A D, Parsons, R D and Wolfendale, A W, ’Possible cosmic ray signatures in clouds ?’, J. Phys. G: Nucl., Part. Phys., (2009a), 322495/PAP/158830.

17. Erlykin, A D, Gyalai, G, Kudela, K, Sloan T, and Wolfendale A W, ‘On the correlation between cosmic ray intensity and cloud cover’, J.Atmos.Sol-Terr. Phys. (2009b), doi:10.1016/j.jastp.2009.06.012.

18. Frisch, P C, 'Characteristics of nearby Interstellar Matter', Space Science Rev., 72, (1995) 499.

19. Gurevich, A V and Zybin, K P, ‘Runaway breakdown and electric discharges in thunder-storms’, Physics Uspekhi, 44, (2001), 1119.

20. Gurevich, A V, Karashtin, A N, Ryabov, V A, Chubenko, A P and Shepetov, A L (2009), ‘Non-linear phenomena in the ionospheric plasma. Effects of cosmic rays and runaway breakdown on thunderstorm discharges’, Physics Uspekhi, 52, (2009) 735.

21. Haigh, J D, 'The impact of solar variability on climate', Science, 272, (1996) 981.

22. Harrison, R G and Ambaum, M P H, 'Enhancement of cloud formation by droplet charging', Proc. Roy. Soc. a, doi:10.1098/rcpa 2008.0009.

23. Hofman, D J and Rosen, J M, 'Condensation nuclei events at 30 km and possible influences of cosmic rays', Nature, 302, (1983) 511.

24. Hoyle, F and Wickrama-singhe, N C, ‘Our place in the Cosmos’, publ.J.M.Dent, Phoenix Publ.(1993) ISBN 978 1 861978486.

25. Hunter, S D, Bertsch, D L, Catelli, J R et al., 'EGRET observations of the diffuse gamma ray emission from the Galactic Plane', Astrophys. J., 481, (1997) 205.

26. Hu, H, ‘Status of the EAS studies of cosmic rays with energy below $10^{16}$eV’, (2009), arXiv:0911.3034

27. Kniveton, D R, Tinsley, B A, Burns, G B, Bering, E A and Troshichev, O A, ‘Variation in global cloud cover and the fair-weather vertical electric field’, J. Atmos. Solar-Terr. Phys, 70, (2008) 1633.

28. Kudryavtsev, I V and Jungner, H, 'A possible mechanism of the effect of cosmic rays on the formation of cloudiness at low altitudes',Geomagnetism and Aeronomy, 45, (2005) 641.
29. Laken, B, Wolfendale, A W and Kniveton D, 'Cosmic ray decreases and changes in the liquid cloud fraction over the oceans', Geophys. Res. Lett., 36, (2009) L23803.

30. Lastovicka, J and Krizan, P, 'Geomagnetic storms, Forbush decreases of cosmic rays and total ozone at northern middle higher latitudes', J. Atmos. Solar-Terr. Phys. 67, (2005) 119.

31. Lim, Guy-Ho and Shim, Tae-Hyeon, 'The Climate based on the Frequency of Meteorological Phenomena in the Annals of Chosun-Dynasty', Science in China (B), 38, (2002) 4, 343.

32. Looper, M G, 'Maya Art and Kingship at Quirigua', Univ. of Texas Press, (2003).

33. Lu, A B, 'Correlations between cosmic rays and ozone depletion', Phys. Rev. Lett., 102, (2009) 118501.

34. Marsh, N and Svensmark, H, 'Low cloud properties influenced by cosmic rays', Phys. Rev.Lett., 85, (2000) 5004.

35. Melott, A L, Overhott, A C and Pohl, M, 'Testing the link between terrestrial climate change and Galactic spiral structure', Astrophys. J., 705, (2009) L101.

36. Miller, S L, 'A production of amino-acids under possible primiteve earth conditions', Science 117, (1953) 528.

37. Ney, E P, 'Cosmic Radiation and the Weather', Nature, 183, (1959) 451.

38. Odzimek, A, Loster, M and Kubicki, M, 'EGATEC - a new high resolution engineering model of the global atmospheric electric circuit. I. Currents in the lower atmosphere', J. Geophys. Res. (2009), in press.

39. Palle Bago, E and Butler, C J, 'The influence of cosmic rays on terrestrial clouds and global warming', Astronomy and Geophysics, 41, (2000) 18.

40. Parman, S W, 'Blood from a stone: water and life on the early Earth', 'Water on Earth and Beyond', 22, 23 September (2009), Durham University water.workshop:dund.ac.uk.

41. Pudovkin, M I, Vinogradova, N Ya and Veretenenko, S V, 'Variations of atmospheric transparency during solar proton events', Geomagn. Aeron., 37, (1977) 2, 124.

42. Rogers, M J, Sadzinska, M, Szabelski, J, van der Walt, D J and Wolfendale, A W, 'A comparison of cosmic ray energy spectra in Galactic spiral arm and interarm regions', J. Phys.G: Nucl.,Part. Phys., 14, (1988) 1147.
43. Rycroft, M J, Harrison, R G, Nicoll, K A and Marcev, E A, ‘An overview of Earth’s Global Electric Circuit and Atmospheric Conductivity’, (2008), Planetary Atmospheric Electricity, Eds.F.Leblanc et al., Springer, doi:10.1007/978-0-387-87664-1.6.

44. Satori, G, Lemperger, I and Bor, J., ‘Modulation of Annual and Semian-nual areal variations of global lightning on the 11-y solar cycle’ (2007), 2nd Int. Symp. on Lightning Physics and Effects, Vienna; European COST action, p.18.

45. Saunders, R H and Prendergast, K H, 'The possible relation of the 3-kpc arm to explosion in the Galactic nucleus', Astrophys. J., 188, (1974) 489.

46. Shaviv, N J, 'Cosmic ray diffusion from the Galactic Spiral Arms, iron meteorites and a possible climatic connection’, Phys. Rev. Lett., 89 (2002), 051102.

47. Shaviv, N J, 'The spiral structure of the Milky Way, cosmic rays and ice age epochs on Earth’, New Astronomy, 8, (2003) 39.

48. Shumilov, O I, Kasatkina, E A, Henriksen, K and Vashenyuk, E, 'Enhancement of stratospheric aerosols after solar proton event', Ann. Geophysicae, 14, (1996) 1119.

49. Sloan, T and Wolfendale, A W, 'Testing the proposed causal link between cosmic rays and cloud cover', Environmental Research Letters, 3, (2008) 024001.

50. Starkov, G V and Roldugin, V K, 'On the relation between the variations in the atmospheric transparency and geomagnetic activity', Geomagn. Aeron., 34, (1994) 4, 156.

51. Stozhkov, Yu I, 'The role of cosmic rays in the atmospheric process’, J. Phys.G: Nucl., Part. Phys. 29, (2003) 913.

52. Svensmark H, 'Cosmoclimatology : a new theory emerges’, News Rev. Astron. Geophys., 48, (2007) 1.18.

53. Svensmark, H, Bondo, T and Svensmark, J, 'Cosmic ray decreases affect atmospheric aerosols and clouds’, Geophys. Res. Lett., 36 (2009) L15101.

54. Svensmark, H and Friis-Christensen, E, J. 'Variation of cosmic ray flux and global cloud coverage: a missing link in sun-climate relationships', Atmos. Solar-Terr. Phys., 59, (1997) 1225.

55. Tinsley, B A, Burns, G B and Zhou, Limin, 'The role of the global electric circuit in solar and internal forcing of clouds and climate', Advances in Space Research 40, (2007) 1126.

56. Tinsley, B A, 'The global atmospheric circuit and its effect on cloud microphysics’, Rep. Progr. Phys., 71, (2008) 066801.
57. Tonev, P and Velinov, P I Y, 'Quasi-electrostatic fields in the near-earth space produced by lightning and generation of runaway electrons in ionosphere', Adv. Space Res., 31, (2003) 1443.

58. Usoskin, I G and Kovaltsov, G A, 'Cosmic ray induced ionization in the atmosphere: full modeling and practical applications', J. Geophys. Res., 111, (2006) D21206.

59. Usoskin, I G, Tylka, A J, Kovaltsov, G A and Dietrich W F, 'Long-term geomagnetic changes and their possible role in regional atmospheric ionization and climate', Proc. 31st ICRC, Lodz (2009) SH3.5-105.

60. Vahia M N, 'Long term variability of heliopause due to changing conditions in local interstellar medium', In: 'Solar Influence on the Heliosphere and Earth’s environment: Recent progress and prospects', ed. N.Gopalswamy and A.Bhattacharya, ILWS and Indian Institute of Geomagnetism, Mumbai, India, (2006), 189.

61. Velinov, P I Y, Mishev, A and Mateev, L, 'Model for induced ionization by galactic cosmic rays in the Earth atmosphere and ionosphere', Adv. Space Res., 44, (2009) 1002.

62. Voiculescu, M, Usoskin, I G and Mursula, K, 'Different response of clouds to solar input', Geophys. Res. Lett., 33, (2006) L21802.

63. Wdowczyk J and Wolfendale A W, 'Cosmic Rays and Ancient Catastrophes', Nature, 268, (1977) 510.

64. Williams, E R, 'Encyclopedia of Atmospheric Sciences', ed. J.R.Holton, J.A.Pyle, J.A.Curry (Academic Press, New York), (2002) 724.

65. Wolfendale, A W, 'Cosmic Rays at Ground Level', Ed. A.W.Wolfendale, Inst. of Physics, (1973) 1.

66. Yukhimuk, V, Roussel-Dupre, R A, Sympalisty, E M D and Taranenko Y, 'Optical characteristics of blue jets produced by runaway air breakdown, simulation results', Geophys. Res. Lett., 25, (1998) 3289.
Captions to Figures

Figure 1 Short-term variations of cosmic rays over a period of 1 million years using our statistical model (Erlykin and Wolfendale, 2001a). The ‘bin width’ is 1000y. The results relate to a model with an energy dependent diffusion coefficient having exponent $\delta = 0.5$ (in the relation diffusion coefficient $D \propto E^\delta$, where E is the proton energy), and supernova remnants accelerating CR protons up to a maximum energy of 10 PeV. The intensities at 1 PeV and 10 PeV are displaced upwards by 2 and 10 respectively for ease of discrimination.

Figure 2 The ‘$log N, log S$’ plot for peak heights from Figure 1, 68 in all. Each peak has height ‘$S$’ = the ordinate in Figure 1 minus the previous minimum. The ordinate, $N(> S)$, is scaled so that it represents the number of peaks per hundred million years of height $> S$. The lines are simple parabolic fits to the points. Importantly, in the middle region ($log S \sim 1$), they have slope $\gamma = 1$, appropriate to a 2-dimensional distribution of sources, whereas at high values of $S$ they are as appropriate for a 3-D distribution of sources.

Figure 3 Fraction of time (in the My sample) for which the intensity is $\tau$ times larger (in logarithmic units) than the overall median value and the fraction for which the intensity is $\tau$ times smaller. In terms of evolutionary effects, the excesses and deficits are both of importance.

Figure 4 As for Figure 1 but for a bin width of 10,000 y.

Figure 5 The CR intensity from a single supernova at 300 pc from the Earth. Our estimated range of the ‘present time’ is indicated by vertical dotted lines.
SHORT-TERM VARIATION OF COSMIC RAYS ($\delta = 0.5$)

(intensities at 1 PeV and 10 PeV are increased by 2 and 10 respectively.)

Fig. 1
Fig. 3
SHORT-TERM VARIATION OF COSMIC RAYS ( $\delta = 0.5$ )
(intensities at 1 PeV and 10 PeV are increased by 2 and 10 respectively)

$\log(10^3 E_0^3)$, cm$^{-2}$s$^{-1}$sr$^{-1}$GeV$^{-2}$

Time, years

Fig. 4
TIME VARIATION OF COSMIC RAYS FROM THE SINGLE SUPERNOVA (R = 300 pc, δ = 0.5)

ENERGY SPECTRUM AT R = 300pc AT DIFFERENT TIMES FROM THE EXPLOSION
(numbers near curves show the time after the explosion in kyear)

Fig. 5