Time variability of high energy cosmic rays

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Abstract

Our model involving cosmic ray acceleration in supernova remnants has been used to predict cosmic ray intensities over long periods of time on a statistical basis. If, as is highly probable, extensive air showers caused by PeV cosmic rays are needed to initiate terrestrial lightning then past dramatic changes in PeV intensities may have had important biological effects.

The model has been used to estimate the manner in which the PeV cosmic ray intensity at Earth has varied over the past tens of thousands of years.

1 Introduction

Over the 4.5By since the formation of the Earth the astronomical environment has been variable and, with it, the cosmic ray spectrum. There are three main sources of variability: the Geomagnetic field, the Sun (by way of the solar wind) and the presence of nearby cosmic ray (CR) sources. The first two relate to variations of the low energy particles, principally below 10 GeV, and the last-mentioned to all energies.

In addition to an interest in its own right, the variation of CR energy spectrum with time has relevance to atmospheric properties and thus (perhaps) to the human condition. Concerning solar effects, the most prominent variation is the 11-year ‘Solar Cycle’. An effect on terrestrial climate is debatable; whereas some (eg Svensmark, 2007) attribute the correlation of CR
intensity, by way of neutron monitor measurements, with low cloud cover to ‘cause and effect’ others, including ourselves (eg Erlykin et al, 2009) differ. Nevertheless, in the upper atmosphere there are genuine signals of changes (ionsphere, ozone) which can be attributed to the occasional high fluxes of solar protons.

Our work reported here relates to higher energies than those concerned with solar effects, specifically \(10^{14}\text{eV}\) and above. There is possible relevance to the atmosphere (and humans) by way of the likely role of such particles in the initiation of lightning (eg Gurevich and Zybin, 2001, Chubenko et al., 2009, Gurevich et al., 2009, Chilingarian et al., 2009). The idea is that the leader lightning stroke is initiated by runaway electrons which are part of extensive air showers (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 members of EAS).

Our own estimates confirm that low energy CR do not correlate with lightning frequency. The frequency of lightning strokes vs. geomagnetic rigidity cut-off has the best fit slope index of 0.23±0.14 to be compared with -0.8 expected if the neutron monitor counting rate was relevant.

On the other hand our estimates of the zenith angular distribution of lightnings is close to the expected for EAS. The mean zenith angle of the leader stroke is 17±3 degrees to be compared with 19 degrees for EAS. The mean zenith angle for the main strokes is 20±2 degrees.

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 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. Changes consequent upon ‘our’ very large changes in CR intensity could be profound.

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 caused quite complex molecules to be generated (monomers, RNA etc) which were necessary pre-cursors of elementary life. Thus, lightning could, conceivably, have provided the required discharges.

Later, when ‘life’ was advanced, lightning could 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 could have been important.

Even if none of the above effects turn out to be important, a knowledge of the past history of the intensity of high energy CR (HECR), by which we mean 10\(^{14}\)eV and above, is of considerable interest.

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 model of CR acceleration (Erlykin and Wolfendale, 2001b). We then go on to make an examination of the manner in which the HECR intensity on earth has varied in the recent past - some 30,000 y - assuming that our Single Source Model of the ‘knee’ in the spectrum at \(\sim 3 \cdot 10^{15}\) eV (Erlykin and Wolfendale, 1997) is correct.

2 Variations of cosmic rays over the past million years using the results of a Monte Carlo analysis

2.1 Time Profiles as a function of energy

Figure 1 shows a typical time-profile for different energies. Protons are assumed in the calculations but the results can be applied to other nuclei by simple rigidity-transformation. It will be noted that in addition to the rare upward excursions, which are particularly marked at the highest energies (taken here as 10 PeV) there are long periods - by chance - when the average level is well below the mean. Larger variations of CR at higher energies are the consequence of the stochastic nature of supernova explosions in space and time. Recent and closer explosions produce CR with flatter spectrum not distorted yet by propagation effects (the slope index is \(\sim 2.1\) compared with \(\sim 2.7\) for the background) and their excess contribution is more pronounced at higher energies.

Starting with the positive excursions, we define ‘peaks’ above nearby minima and give the usual log N - log S 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 1000 y. The lines drawn in Figure 2 are simple parabolic ‘best-fits’. In the
Figure 1: Short-term variations of cosmic rays over a period of 1 million years, using our statistical model (Erlykin and Wolfendale, 2001a). The time interval is 1 ky. The results relate to the EW model with an energy dependent diffusion coefficient having exponent $\delta = 0.5$ 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.

‘middle region’, say log $S = 1$ 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 further away than the half-thickness of the SNR distribution (hwhm $\simeq 250$ pc). At $S$ values below 1 the curvature arises from 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 250 pc and the distribution of relevant sources tends to three-dimensional.

Of particular interest is the extension to cover a period of $10^8$ years, the likely period $\simeq 3.8$- 3.9 Gy ago (or somewhat longer) when pre-biotic life formed on Earth. We note that of order one peak would occur for energy 10 PeV and above with intensity some 3,000 times the datum. Taking the median value of log $I$ - 1.69 the enhancement is a factor of about 60. Such
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. N(>S) is the number of peaks per My of height >S. The lines are simple parabolic fits to the points. Importantly, in the middle region (log S ∼ 1) they have slope γ = 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.

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an enhanced intensity would continue for a few thousand years.

The model ignores the fact that SN II (the type responsible for the CR in question) are formed predominantly in Galactic Spiral Arms, which are crossed by the solar system every $10^8$ years. The result is simply to redistribute the pattern in time, without having an effect on the mean frequency of the large intensity excursions.

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 $10^6$ y. This is given in Figure 3 for 10 PeV. It will be noted that for 10% of the time
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.

The intensity will be about ten times the median and for 10% of the time, the intensity would be about 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 10,000 years. The 10 PeV peaks are typically 5 times smaller than in Figure 1. The equivalent of Figure 2 would give an enhancement by about a factor 10, lasting 10,000 y every 100 My.

3 The likely intensity in the immediate past

In our earlier work (Erlykin and Wolfendale, 2003), we identified the ‘single source’, responsible for the ‘knee’ in the cosmic ray spectrum as probably
being in the distance range 250 - 400 pc and being of age in the range 85 to 115 ky. Figure 5 shows the results of our calculations for a distance of 300 pc and the range of ages just indicated. It will be noted that the ratio of the intensity (for 10 PeV) 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 should have been significantly higher than at present. It is conceivable that a study of ancient Chinese and Korean records would give useful records of past lightning frequencies.

4 Discussion and Conclusions

The results are, from the CR point of view, straightforward: considerable fluctuations in PeV CR intensities should occur over long periods of time (My). The corresponding changes in the total CR flux would be very small. At high energies, in fact, the variations will be bigger than quoted if, as
Figure 5: The CR intensity from a single SN at 300 pc. Our estimated range of the ‘present time’ is indicated by vertical dotted lines in the upper panel.
seems possible, the diffusion coefficient in the ‘local bubble’ in the interstellar medium, in which we reside, is 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 UHECR intensity fluctuations, would also have dramatic ‘gamma ray flashes’ which could also have a dramatic effect on the Earth, not least on the ozone layer (eg. Wdowczyk and Wolfendale, 1977 and references therein).

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

At later stages, when life was evolving, the occasional lightning excesses with increased production of NO\textsubscript{x} could have had pronounced positive effects on vegetation and negative effects on humans. However, evolutionary spurts may have occurred for these long periods when the 10 PeV intensity was low.

The claimed PeV increase in the past could (over,say, 5000 years) conceivably be found in historical records of changes in lightning rates.

We know of no work related to global circuit caused by dramatic changes in the HECR rate. There may be other consequences beside a (presumed) change of the frequency of lightning strokes such as their individual strengths - and other atmospheric phenomena.

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