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Cosmic rays from SNR, I: Spatial and temporal variations

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Abstract. It is generally agreed that SNR contribute many Cosmic Rays below about 10 PeV. A Monte Carlo analysis has been made to give the expected spatial and temporal variations of the flux at earth and in the local ISM. There is found to be no disagreement with such observations as have been made.

1 Introduction

The Monte Carlo analysis described in detail by us elsewhere (Erlykin and Wolfendale, 2001) involves SN at the rate of 10^{-2} y^{-1}, distributed randomly in the Galaxy both in space and time, from which cosmic rays may diffuse to the earth. It is assumed that the acceleration proceeds within the remnant by shock acceleration (Axford, 1981 and later work) until the remnant reaches a radius of 100 pc, after which the particles escape freely. The diffusion is characterised by a mean lifetime $T(E) = 4 \times 10^7 E^{-0.5}$ y where E is the energy measured in GeV.

For each SNR configuration we determine the energy spectrum for 3 points in the Galactic plane (the analysis is 2-D) and repeat the procedure at time intervals of 10^4 y and 10^5 y.

2 Spectral changes in the Galaxy: the Gamma Ray and Synchrotron evidence

Large scale spectral changes for the gamma ray spectrum were identified by Bloemen, 1987; Rogers et al., 1988 and van der Walt and Wolfendale, 1988, but these are usually attributed to changes in the electron to proton ratio with increasing Galactocentric radius. On a smaller distance scale there are reports from Fatoohi et al. (1995) and Chi et al. (1995) that over distance scales of order 1 kpc there are spectral changes which indicate that the primaries (protons) have dispersion of the exponent for the energy spectrum, γ given by $\Delta\gamma \simeq 0.06$, with a similar result for electrons (the energies here being less than a few GeV).

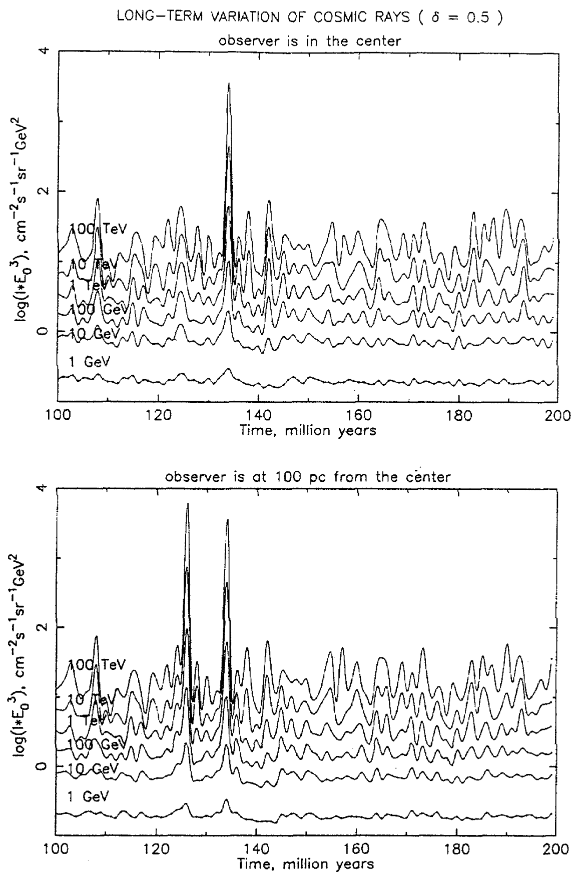

Fig. 1. Long term intensity variations, with a time interval of 10^6 y, as a function of energy for two locations, separated by 100 pc (by 'the centre' is meant the sun).

For synchrotron radiation from electrons, the work of Lawson et al. (1987) yields spectra variations for electrons (of energy ≈ 15 GeV) given by $\Delta\gamma_e \simeq 0.07$.

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The present work yields $\Delta\gamma_p \sim 0.025 - 0.05$ for distance ranges 100-1000 pc from the sun; viz. values not inconsistent with the observations, particularly when experimental errors are borne in mind. For the energies in question we expect $\Delta\gamma_e \simeq \Delta\gamma_p$.

3 Temporal changes of the CR intensity at the Earth

3.1 Comparison with cosmogenic nuclides

Many experiments have been carried out with cosmogenic nuclides in both terrestrial samples (deep sea cores, Antarctic ice) and non-terrestrial samples (lunar cores, meterorites) and variations in the CR flux over a variety of time scales have been determined. In fact, most (and perhaps all) of the time-variations recorded so far can be attributed to solar and geo-magnetic effects and only upper limits can be given for variations in the interstellar spectrum, this latter being the object of the present Monte Carlo studies.

Figure 1 shows results for 1 My intervals and Figure 2 the variations for 10^4 y variations.

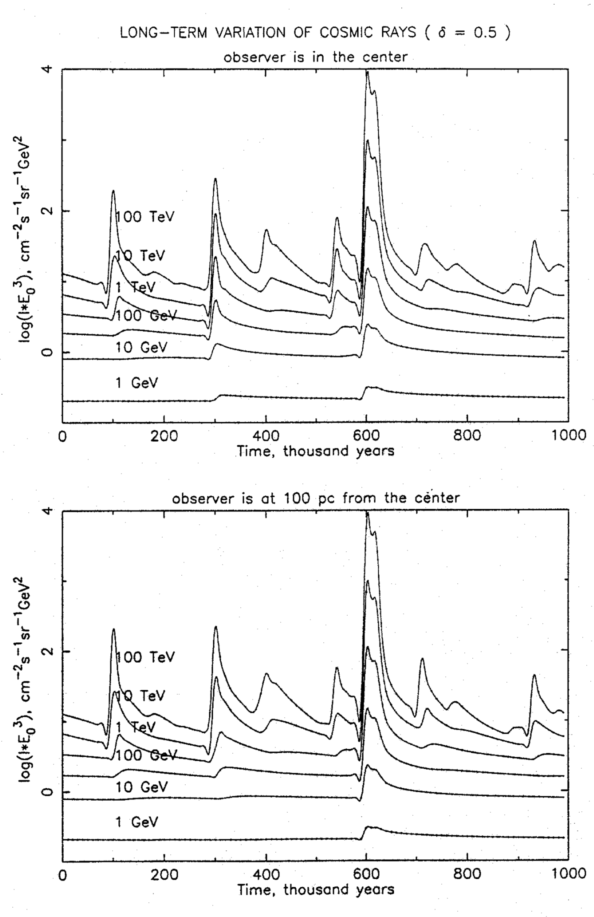

Fig. 2. Long term intensity variations, with a time interval of 10^4 y, as a function of energy for two locations.

None of the variations is inconsistent with the upper limits for the cosmogenic nuclei: $\sim \pm 30\%$ for averaging times $\sim 5 \times 10^4$ y and somewhat similar results for longer times, the effective energy being about 10 GeV.

3.2 Probability distributions for the intensity changes

3.2.1 Low energies

Recent results (Stozhkov et al., 1999; Glushkov and Pravdin, 2001) have given evidence for possible changes of intensity over much shorter periods and it is of interest to study our results for the shortest time interval (10^4 y) in more detail. Figure 3a gives the probability distributions; also shown, in Figure 3b, are probabilities of there being a change of more than 10% per 10^4 y as determined from Figure 3a.

To compare with experiment, Stozhkov et al. analyzed the world's data from neutron monitors and found a slow downward trend, for particles of energy 1–10 GeV, of magnitude $0.05 \pm 0.04\%$ per y (individual estimates have much smaller errors but the spread is such as to indicate the value shown, for the mean). Our estimates, for 10 GeV, from Figure 3 are seen to be considerably smaller. There are two possibilities to account for the discrepancy: the model is inappropriate or the observations are due to a slow change in the solar wind and not to changes in the interstellar spectrum of the type studies here. Concerning the model, it is true that if the solar system is on the inner edge of the shell of a very recent, nearby SN, such that the Bohm diffusion is relevant (i.e. the diffusion mean free path is equal to the Larmor radius) then the predicted time variability could be as high as is apparently observed. However, a worry is that indications of our being so close to an SNR shell from observations of other astronomical phenomena seem to be absent. The other explanation seems more likely, not least because of the summary of the world's data on the measured rate of decline of the CR flux as a function of threshold rigidity shows no sign of the expected increase if it were the interstellar intensity that was varying. In fact, there is a big dispersion in the values from one rigidity to another and, if anything, the rate of decline of flux is falling with increasing rigidity threshold rather than rising. Such a fall is, in fact, suggestive of an explanation in terms of solar variability.

3.2.2 Ultra-high energies

Turning to the highest energies, the work of Glushkov and Pravdin refers to energies above 10^{18} eV; clearly the SNR model, as formulated by us, is not valid here but an indication of what might be expected from Galactic sources comes from extrapolating the results above the PeV region. The logic behind such an approach is that if SN are involved in some way in the acceleration of these particles — e.g. a special category in which the magnetic field in the remnant is amplified to dramatically high values (Lucek and Bell, 2000) — these sources will be rare and an extrapolation is roughly valid, making allowance for the probability of such sources. In Figure 3 we have extrapolated in this way at the 10% level, i.e. if *all* SN were in the very energetic category then there would be a 10% probability of being on this line. If, however, the very energetic category comprised 20% of the total SNR then the extrapolation would need to be reduced by 5. However, the higher density of local SN over the past 10^6 My (Grenier and Perrot, 1999) by a factor 4 compared with the long term Galactic average means that the line would rise again, somewhat.

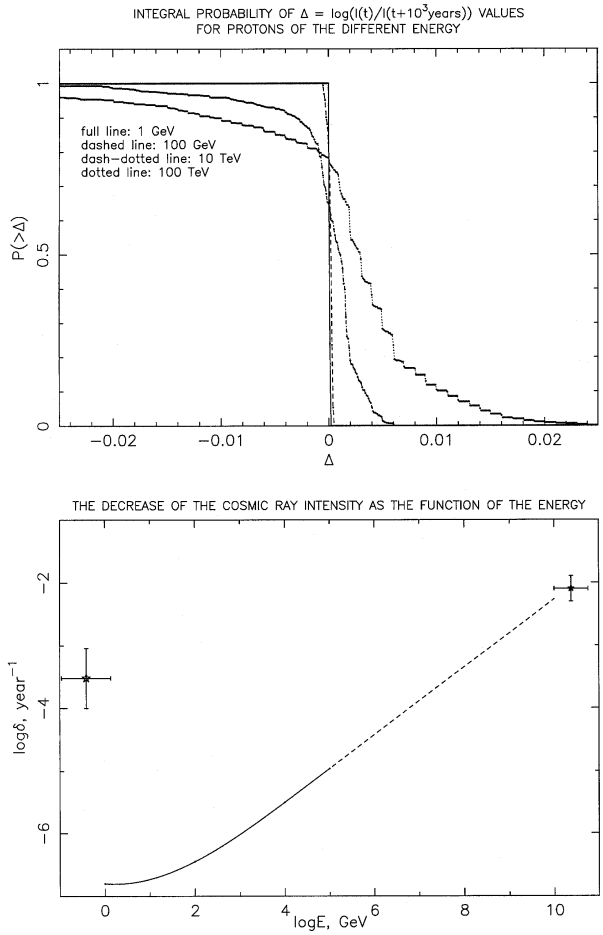

Fig. 3. (a) Probability distributions for time intervals of 10^3 y. (b) The probability of a change of 10% in intensity over 10^3 y, as a function of energy. The line is extrapolated beyond the maximum energy (4×10^5 GeV) appropriate to the standard SNR model; its validity is discussed in the text. The experimental points are: (left) Stozhkov et al. (1999), (right) Glushkov and Pravdin (2001)

From the standpoint of probability alone, a slow reduction in intensity with time cannot be ruled out; remarkably, our extrapolated line passes through the experimental value! However, several points must be made:

(i) It is usually assumed that above the ankle most of the particles are extragalactic. In the scenario just considered they would be Galactic. In fact, if a 'local' source were after all responsible the ankle would have a ready explanation.

(ii) The biggest problem is probably the lack of a dramatic anisotropy of arrival directions. Specifically we would expect most of the particles above 10^{20} eV to 'point back' to one source; they do not. It might be possible to invoke the 'Giant Halo' (Wdowczyk and Wolfendale, 1995) and to hypothesise that all the SNR particles are heavy nuclei so as to near-isotropise the arrival directions but there is a problem with the very large magnetic energy needed for the Giant Halo.

There is urgent need to see if other giant EAS arrays show a similar fall in intensity with time. Configuration would give a dramatic impetus to UHE cosmic ray studies.

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