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LONG TERM VARIABILITY OF THE COSMIC RAY INTENSITY

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1. Introduction. In a previous paper Bhat et al.(1) assess the evidence for the continuing acceleration of cosmic rays in the Loop I supernova remnant. The enhanced gamma-ray emission is found consistent with the Blandford and Cowie (2) model for particle acceleration at the remnant shock wave. We now consider the contributions of other supernovae remnants to the Galactic cosmic ray energy density, paying particular attention to variations in the energy density and anisotropy of cosmic rays accelerated by local supernovae (<100pc). The results are compared with geophysical data on the fluctuations in the cosmic ray intensity over the previous one billion years.

2. Shock Acceleration In Supernova Remnants. Blandford and Cowie have applied shock acceleration considerations to supernovae remnants exploding in the hot ISM. Assuming a proton/electron ratio 10:1, a preshock factor ~ 1 and an ISM magnetic field of $\sim 1\mu$ gauss, we get from Blandford and Cowie the total energy in relativistic particles E within the remnant as

$$E(\text{ergs}) \simeq 2.0\times 10^{48}\, R_1^{2.5} \qquad (1)$$

where the inital supernova energy $\sim 10^{51}$ ergs and R_1 is the remnant radius in units of 10 pc. During the Sedov phase of the expansion the radius of the remnant is related to its age t by

$$t \simeq 3.2 \times R_1^{2.5} \qquad (2)$$

where t is in units of 10^5 years. This is consistent with the previous assumptions about Loop I having an age of 4×10^5 yr and a radius of 110 pc. The efficiency of the mechanism increases with radius, provided the shock is strong. Beyond this size the remnant continues to expand and the particles are assumed to lose their energy adiabatically. We consider three cut-off radii for the acceleration: 50,75 and 100 pc ; corresponding to 10%, 30% and 50% conversion efficiency into cosmic rays.

3. The Monte-Carlo Model. We consider a spherical region ($r<100$pc) around the Sun and calculate the cosmic ray energy density at the centre due to supernovae events occuring randomly in time and space. For type II supernovae we adopt a mean Galactic rate of 1 per 100 yr. This corresponds to a mean explosion rate of 0.066 per 10^5 yr within the local volume. Each simulation covers a 10^9 yr period, with a temporal resolution of 10^5 yr. We do not consider here possible variations in the rate due to motions of the Solar system through spiral arms.

In each time interval the number of supernovae occurring within 100pc is sampled from a Poisson distribution and these are assigned random positions. The mean local energy density is derived from Eq. 1 allowing for the Sedov phase propagation of the remnant, Eq. 2. The three cases A,B,C (corresponding to efficiency values 10, 30 and 50% respectively) are each simulated 10 times and average energy densities derived. The baseline energy densities are initally assumed to be zero, permitting an absolute determination of the local contributions.

Mean energy densities are derived over time-scales from 0.1 to 100 Myr, and long-term averages for models A,B,C are found to be 0.1, 0.5, 1.0 eV cm^{-3} respectively. The local Galactic energy density is generally taken to be $\sim$1.0 eV cm^{-3}, based on present observation of the cosmic ray and synchrotron spectra. To derive the fluctuation in the local energy density we first require the long-term mean to be 1.0 eV cm^{-3}. To achieve this, the baselines in each model are increased to a corresponding constant level.

We also derive the expected cosmic ray anisotropy as a function of time due to the local supernovae. During the acceleration phase the particles are essentially limited to the downstream region, behind the shock front. The anisotropy amplitude δ is thus determined when the remnant sweeps past the Sun, and is given by

$$\delta = 7.1 \times 10^{-4} \; t^{-0.6} \qquad (3)$$

4. Results. The probability of fluctuations on different time-scales, about a mean of 1.0 eV cm^{-3}, are given in Figure 1. The upward and downward probabilities are given separately for models A,B,C. It is apparent that in all cases there is a greater probability of a downward excursion; a reflection of the low probability for a local supernova event in a given time bin. For model A the probability of upward fluctuations is relatively small, whereas downward excursions, of a statistically small magnitude (<10%), are more prevalent. Model C is considered unrealistic, in that it is very difficult to explain the inferred cosmic ray grammage ($E\sim$few GeV) of 6 g cm^{-2} if the particles originate within 100 pc. This extreme case is included to illustrate overall effect of increasing the net acceleration efficiency.

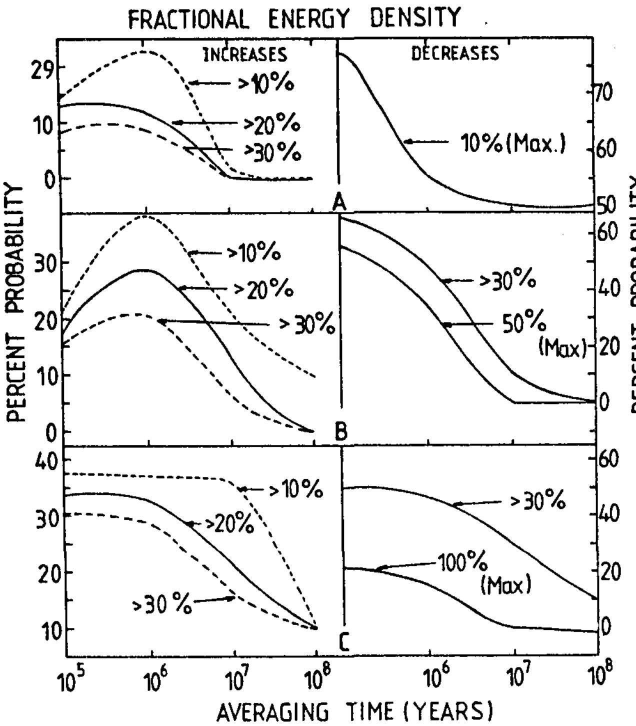

Figure 1

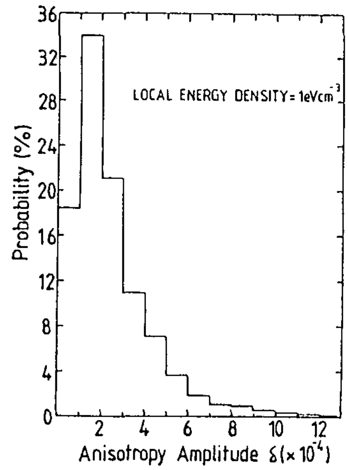

Figure 2

In Figure 2 we show the variation of anisotropies on 10^5 yr time bins, derived from averaging over 10 Monte-Carlo samples of the supernovae spatial distributions. The absolute anisotropies are normalized for the case of 1 eV cm^{-3} local contribution (model C). The absolute values for the other two cases can be derived by scaling to the appropriate mean local energy density.

5. Conclusions. Model B, and to a lesser extent A, predict significant (>20%) increases in cosmic ray energy density on time-scales of a few million years. These results are in agreement with the experimental studies of cosmogenic nuclides by Tokar and Povinec (3) and Voshage (4). However, model B predicts a large decrease in intensity on time-scales of 10^5 yr, suggesting that the presently measured energy density is likely to be less than the true long-term average by up to 50%. While this possibility can not be completly ruled out at present, it seems difficult to reconcile it with the results of high energy (E_γ > 100MeV) gamma-ray observations. From the stand-point of the mean Galactic energy density being ~1.0 eV cm^{-3} model A is more consistent with the observations. If the Blandford and Cowie model is appropriate for the bulk of Galactic supernovae then no more than ~10% of the observed cosmic rays can originate from within 100pc.

References.

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(3) Tokar,S., and Povinec,P., 1983, Proc 18th ICRC, Bangalore, 2, 381
(4) Voshage,H., 1984, Earth and Planetary Sci. Lett., 71, 181