Do extragalactic cosmic rays induce cycles in fossil diversity?

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The idea of cycles in fossil diversity has recently been put on a firm statistical footing, revealing a 62±3-million-year cycle in the number of marine genera[1]. The strong signal requires a periodic process extending back at least 540 My, which is difficult to explain by any terrestrial process. While astro- and geophysical phenomena may be periodic for such a long time, no plausible mechanism has been found. The fact that the period of the diversity cycle is close to the 64 My period of the vertical oscillation of the Solar system relative to the galactic disk[2] is suggestive. However, any model involving cosmogenic processes modulated by the Sun's midplane crossing or its maximal vertical distance from the galactic plane predicts a half-period cycle, i.e. about 32 My. Here we propose that the diversity cycle is caused by the anisotropy of cosmic ray (CR) production in the galactic halo/wind/termination shock[3–5] and the shielding effect of the galactic magnetic fields. CRs influence cloud formation[6,7], can affect climate[7,8] and harm live organisms directly via increase of radiation dose[9]. The CR anisotropy is caused by the galactic north-south asymmetry of the termination shock due to the interaction with the "warm-hot intergalactic medium"[10,11] as our galaxy falls toward the Virgo cluster (nearly in the direction of the galactic north pole) with a velocity of order 200 km/s[12]. Here we revisit the mechanism of CR propagation in the galactic magnetic fields and show that the shielding effect is strongly position-dependent. It varies by a factor of a hundred and reaches a minimum at the maximum northward displacement of the Sun. Very good phase agreement between maximum excursions of the Sun toward galactic north and minima of the fossil diversity cycle further supports our model.

Rohde and Muller[1] performed Fourier analysis of detrended data from Sepkoski's compendium and found a very strong peak at a period of about 62 My. Monte Carlo simulations based on random walk models with permuted steps reveal a 99% probability that any such major spectral peak would not arise by chance. Associating this periodicity with the Solar system crossing the Milky Way spiral arms[13] does not seem very promising. Although the spiral pattern speed is not known, it seems impossible to reproduce both the period and the phase of the diversity cycle[2]. It is very interesting, however, that the 62 My timescale does coincide with the current best value for the period of the oscillation of the Sun in z, the distance perpendicular to the galactic disk. The Sun is currently about 10 pc above the plane (i.e., toward the galactic north), moving away, in an oscillation with amplitude about 70 pc. So far, finding a plausible mechanism tied to this vertical oscillation has been problematic. The primary reason is that midplane crossing (a possible time of enhanced interactions with galactic matter) would occur approximately every 32 My, which is not a spectral feature found in the diversity data. The very same 32 My periodicity, occurs if biological effects are strongest at maximum vertical distance from the galactic plane. It has recently been noted that there is a correlation between genus-level diversity and the amount of marine sedimentary rock outcropping, which is taken as evidence that a sampling bias may have led to the cyclicity signal discussed here[14]. However, this correlation explains the most genus diversity when diversity is correlated with sediment levels of the preceding epoch, which is more suggestive of a common causation between the sea-level change and the biodiversity change.

Cosmic rays (CRs) have strong biological and climatic effects. The ions produced by CRs in the atmosphere increase low altitude clouds[15,16] thus increasing planetary albedo. CR ionization triggers lightning discharges[17], which in turn affect the atmospheric chemistry (e.g., the ozone production by lightning and destruction by lightning-produced nitric oxides). CRs also increase the production of NO and NO_2 by direct ionization of molecules. All these effects should ultimately lead to global climate change[8] and increased UV flux at the surface due to ozone depletion. Last, but not least, CRs produce avalanches of secondary energetic particles[9], which can be dangerous and even lethal to some organisms. If the energy of the primary is below 10^{14} eV, only energetic muons can arrive the Earth surface (some of the muons decays into electrons and positrons). Primaries with higher energies are able to produce air showers that reach the sea level and deliver energetic nucleons as well. Overall, secondary muons are responsible for about 85% of the total equivalent dose delivered by CRs. CR products account for $30 - 40\%$ of the annual dose from natural radiation in the US. There is almost no protection from muons because of their very high penetrating depth, ~ 2.5 km in water or ~ 900 m in rock. CRs are therefore a source of mutations, cancer, etc. even for deep-sea and deep-earth organisms. Note that ideas that a variable CR flux can have strong terrestrial effects has been discussed in the context of supernova explosions[18] and the Sun's motion in the local interstellar medium[19]. These models produce variations which occur randomly in time and on time-scales of hundreds of thousands of years, hence they fail to explain a much longer periodic signal.

Low-energy CRs with 10^{10} eV $\lesssim E \lesssim 10^{15}$ eV (below the "knee") are thought to be produced by galactic sources: supernova explosions, supernova remnant shocks, pulsars[18,20], whereas higher-energy CR flux is dominated by particles accelerated in the giant galactic halo by the shocks in the galactic wind[21,22] and at the termination shock[20]. The galactic termination shock occurs when the fast, supersonic galactic wind interacts with the ambient intergalactic medium, very much like the Solar wind termination shock forms on the outskirts of our Solar system[23]. The position of the shock, which strongly depends on the properties of the "warm-hot intergalactic medium"[10,11,24] (WHIM) and the wind speed, has been estimated[20] to be $R \sim 100 - 200$ kpc for the wind speed $V \sim 300 - 500$ km/s. For these parameters and the Bohm diffusion coefficient, the flux of extragalactic (EG) CRs with $E < E_c \sim 10^{15}$ eV was expected to be attenuated by strong outward advection[22]. However, the first measurement[5] of the wind velocity yielded a much smaller value, ~ 100 km/s (less than the escape velocity from the galaxy). This puts the shock a factor of ten closer, hence decreasing the advection cutoff energy, E_c, by a factor of 30. Moreover, using a more realistic dependence of the diffusion coefficient on particle's energy, $D \propto E^s$ with $s \simeq 0.3 - 0.6$ (for Bohm diffusion, $s = 1$), yields the overall decrease of E_c by a factor of 10^3 to 10^5. Thus, the galactic termination shock should be a natural source of EG CRs with energies as low as $\sim 10^{10} - 10^{12}$ eV, i.e., those which produce muon showers in the Earth atmosphere. This EG component is, likely, subdominant at the present location of the Sun because of efficient shielding by galactic magnetic fields, but can be dominant at large distances from the galactic plane, as we will show below.

The global geometry of the termination shock causes the anisotropy of EG CRs around the Milky Way. In turn, the interaction of the gaseous envelope of the galaxy with the WHIM determines the shock geometry. The WHIM was formed by shock-heating in the early stages of cosmological structure formation and should pervade the filaments predicted to form[25] in the ”Cold Dark Matter” scenario. In the nonlinear stage of the structure formation galaxies fall toward galaxy clusters. In particular, our galaxy moves at the speed of $\sim 150 - 200$ km/s toward the Virgo Cluster[11,12,26], which is located on the sky close to the galactic north pole[24]. The local WHIM is substantially pressure supported, thus having smaller infall velocity. Motion of the galaxy through WHIM, at even moderate relative velocity, pushes the termination shock close to the north galactic face. The even more than moderate motion of the Solar system through the local interstellar medium, ~ 23 km/s (c.f., the Solar wind speed is ~ 700 km/s), produces strong asymmetry, with the shock distance in the “nose” and “tail” directions differing by more than a factor of two[23]. Therefore, the EG CR flux incident on the northern galactic hemisphere must be substantially (perhaps, orders of magnitude) larger than in the southern hemisphere.

In order to see substantial periodic variations in the biosphere, and hence in the fossil record, the flux of CRs should have strong variation as well. We demonstrate now that the shielding effect provided by the galactic magnetic fields against EG CRs does produce the required variation.

The propagation of CRs with energies below the knee in the galaxy is diffusive. The Larmor radii of the particles are smaller than the field inhomogeneities, so the particles nearly follow field lines. These fields are turbulent[27,28], hence the effective diffusion[29]. One often assumes the Bohm diffusion coefficient for this process. As extragalactic CR particles diffuse through the galaxy (in our case, in the vertical direction, from the north face to the south), their density decreases, thus resulting in shielding. A naive application of the standard diffusion approximation yields a linear variation of the CR density as a function of z. Then the maximum variation of the CR flux on Earth would be $\sim \Delta/H \sim 5\%$, – too small to have strong impact on climate and biosphere (where $\Delta \simeq 70$ pc is the maximum vertical displacement of the Sun and $H \sim 1.5$ kpc is the exponential scale-height of the galactic disk region dominated by magnetic fields[28]). However, the magnetic field fluctuations in the galaxy are of high-amplitude[28], with $\delta B/\langle B\rangle$ ~few, and are likely Alfvénic in nature. Therefore, the effects of particle trapping and mirroring[29] are of great importance.

We know of no discussion of the effects of trapping and repeated mirroring in the presence of a mean field gradient (as in a galaxy) combined with random walk resulting in *asymmetric* diffusion, in which the probability of particle motion in forward and backward directions are unequal. This should not be confused with the standard diffusion, in which the probabilities are equal, though the diffusion coefficient can be a function of position, in general. To estimate the magnitude of the asymmetry, recall that the amplitude of turbulent magnetic fluctuations is maximum on large spatial scales and decreases as magnetic energy cascades to small scales. Hence trapping by large-amplitude waves occurs on scales comparable to the field correlation length[27], hence $\lambda \sim 10$ pc. (In fact, the mean-free-path, λ, increases with particle's energy; the value of 10 pc is for a 10 GeV particle.) Trapping is intermittent and transient because large-amplitude, quasi-coherent Alfvénic wave-forms ("magnetic traps" or "magnetic bottles") exist for the Alfvén time. Thus, a trapped CR particle, moving at almost the speed of light, experiences about $N_b \sim c/V_A \sim 3\times 10^4$ bounces (for the interstellar medium field $B \sim 3\ \mu$G and density $\rho \sim 3\times 10^{-24}$ g/cm^3, where $V_A = B/\sqrt{4\pi\rho}$ is the Alfvén speed) during the bottle lifetime. Reflection conditions are determined by the particle loss-cones on both ends of the magnetic bottle. In the presence of a field gradient (B decreasing away from the galactic plane on a distance $H \sim 1.5$ kpc; the precise value of H not known, but it does not significantly affect the results of our model), the loss-cone conditions imply that, on average, more particles are reflected from a higher-field end (that is, which is closer to the galactic plane) than from the lower-field one. From the loss-cone condition, we estimate the reflected fraction in one bounce as $\epsilon_0 \sim \lambda[\langle B\rangle/(\nabla\langle B\rangle)] \sim 10^{-3}$. Since particles also interact with the smaller-amplitude, high-frequency background of short-scale Alfvén waves, the particle distribution function evolves toward isotropization while trapped particles traverse the magnetic bottle. We assume some ten percent efficiency of this process, $\eta \sim 0.1$. This leads to a small "leakage" of particles from the trap, predominantly in the direction away from the galactic plane. The total "leaked out" fraction per the trap lifetime is $\epsilon \sim 1-(1-\eta\epsilon_0)^{N_b}$. A complete calculation of all these processes will be presented elsewhere.

The number density of CRs in the galaxy is found using the one-dimensional (i.e., along z) Markov chain model, shown in Figure 1. The galaxy is represented by N sites, separated by one mean-free-path distance, thus $N \sim H/\lambda$. The two $*$-states at both ends are "absorbers" representing escape of CRs from the galaxy. There is in-flux of CRs, $J_{\rm CR}$, (produced at the termination shock in the northern hemisphere) through the right end. The galactic plane is located half-way between $N/2$ and $N/2+1$ sites. The Sun moves through sites between $N/2-m$ and $N/2+m$, where $m \sim \Delta/\lambda \sim 7$. At present, the Sun is at $z \simeq 8$ pc, which is around site $N/2+1$. The forward and backward transition probabilities are r and g; their subscripts denote position: above (+) or below (−) the plane. By symmetry, $r_+ = g_-,\ r_- = g_+$. At last, the ratio is $g_+/r_+ \sim 1+\epsilon$, with ϵ obtained in the previous paragraph. An analytical solution for the CR density is plotted in Figure 2. The exponential increase of the local CR density with z is seen. For contrast, we also plot the result of the standard diffusion model (i.e., with $\epsilon = 0$). Thus, very strong exponential shielding from EG CRs is found.

Figure 3 shows the detrended fossil genera fluctuation from Ref. [1] and the computed CR flux from our model versus time for the last 500 My. Here we used the best available model data for the solar position z versus time from Ref. [2]. These calculations assume azimuthal symmetry of the Milky Way, so the effect of spiral arm crossing is missing. The oscillation period and the amplitude of oscillation varies in response to the radial motion of the Sun and a higher density toward the Galactic center. The average period, accurate to about 7%[2], ~ 63.6 My coincides within uncertainty with the 62 ± 3 My period of the fossil diversity cycle[1]. We note that the 62 My signal in the fossil record emerges from integration over about 9 periods, and does not coincide in detail with major extinction events. These may result from a combination of stresses including CR flux variation and such other events as bolide impacts, volcanism, ionizing radiation burst from other sources etc. (We note that the K/T extinction[1] coincides within 1 My of mid-plane crossing[2].) Some scatter in the dating leads to a somewhat broadened peak; but such scatter is expected in the period of the solar excursions due to surface density variations in the galaxy[2]. Note that the long-term modulation of CR maxima in Figure 3 is real. It is due to the Sun's radial motion relative to the Galactic center. Hence, one can expect a long-term cycle with a period ~ 170 My in the fossil record, though its amplitude should be small. The amplitude of CR fluctuations is expected to depend on particle energy, the properties of the galactic magnetic fields and turbulence spectrum. The whole process can be accurately modeled using currently available computing resources, thus providing a definitive test to our model. At last, we stress that both the 62 My-period and the phase of the oscillation agree, within the uncertainties. The maximum positive z displacements coincide within a few My of the minima of fossil diversity[1]. The coincidence of the times of the rapid CR flux increase and the on-set times of rapid diversity decline is even stronger, which suggests a trigger-like mechanism driven by EG CRs.

Noting the agreement in period and phase of solar motion in the galaxy with a time series analysis of fossil diversity, we have shown that a substantial flux of cosmic rays should be produced at the galactic north termination shock, and that the galactic magnetic field provides substantial shielding though mechanisms of reflection and scatter, leading to an enhanced cosmic ray exposure at large northward excursions. This provides a natural mechanism for cycles in fossil diversity.

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Author contribution M.V.M originated the idea of enhanced magnetic shielding and performed all calculations of the model, proposed the asymmetric diffusion concept, estimated the termination shock position, the resulting EG CR production anisotropy and the typical CR energies. M.V.M produced all figures and wrote the paper except for references, introduction, and discussion paragraphs, which were written jointly. A.L.M. found the coincidence of both the period and phase of the diversity cycle and the Sun northward excursions, and suggested that the motion of our galaxy in the local WHIM could affect the termination shock geometry. Both authors discussed the results and commented on the manuscript.

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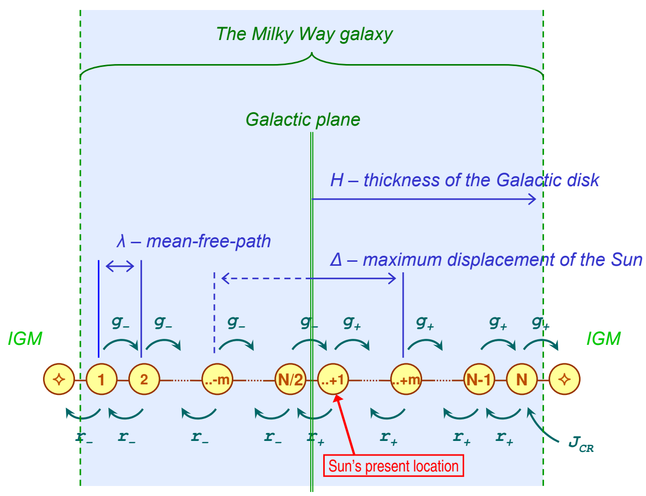

Figure 1: **The galactic Markov chain.** The cartoon represents the Markov chain model used to calculate Cosmic Ray diffusion through the Milky Way galaxy. The chain consists of N normal sites and two absorbing ($*$) sites, which model particle escape. The transition probabilities are r and g; their subscripts denote position: above ($+$) and below ($-$) the galactic plane. The in-flux of CRs is $J_{\rm CR}$. The Sun moves through sites between $N/2-m$ and $N/2+m$ and is presently located near the $N/2+1$ site.

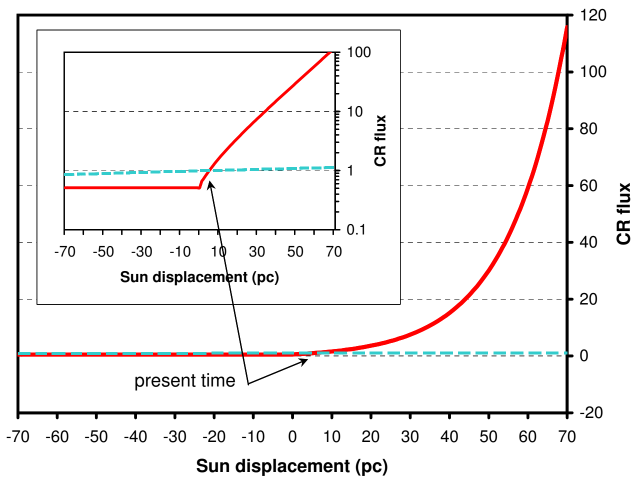

Figure 2: **The extragalactic cosmic ray flux at the Earth relative to the present day value.** The linear plot and the log-linear plot (*in-set*) of the predicted EG CR flux (normalized to the present day value) in the Milky Way galaxy as a function of the distance from the galactic plane (in parsecs) for the asymmetric diffusion model (*solid line*). The standard diffusion model, predicting a 5% increase, is shown for comparison (*dashed line*). Clearly, a hundred-fold increase in the CR flux at the Earth is possible at maximum excursions of the Sun from the galactic plane.

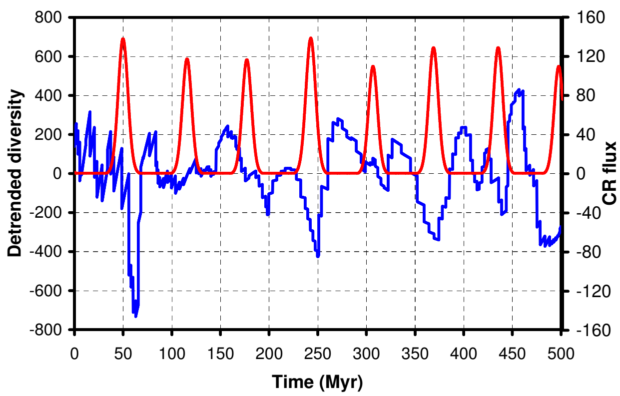

Figure 3: **The diversity variation (from Ref. [1]) and extragalactic cosmic ray flux at the Earth calculated from our model.** The de-trended diversity variation (*blue curve*, *left scale*) as a function of time over-plotted with the normalized cosmic ray flux calculated from our model (*red curve, right scale*). There are no fit (and free) parameters in the model. The minima in the cosmic ray flux coincide maxima of the diversity cycle and vice versa. Note also that the onset times of the diversity decline coincide with moments of the rapid increase of the flux.