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Cosmic rays and the biosphere over 4 billion years

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Variations in the flux of cosmic rays (CR) at Earth during the last 4.6 billion years are constructed from information about the star formation rate in the Milky Way and the evolution of the solar activity. The constructed CR signal is compared with variations in the Earths biological productivity as recorded in the isotope δ^{13}C, which spans more than 3 billion years. CR and fluctuations in biological productivity show a remarkable correlation and indicate that the evolution of climate and the biosphere on the Earth is closely linked to the evolution of the Milky Way.

1 Introduction

Cosmic rays (CR) are a fundamental component of the interstellar medium (ISM). They exert a pressure on interstellar matter against gravitational forces that is on an equal footing with that from gas and magnetic fields. As a result CR are important for the dynamics of the ISM that in turn leads to star formation and ultimately to stars that end their life as supernova. Acceleration of mainly protons and heavier elements by supernova (SN) shock fronts are the main source of CR. The Earth has been embedded in this field of CR since its formation 4.6 billion years ago. The question raised here is whether this variable field has had any detectable consequence for the evolution of Earth.

Several studies suggest that CR currently influence the Earth's climate (Svensmark & Friis-Christensen 1997), and it has been proposed that this is the result of low-level clouds responding to variations in CR (Svensmark 1998; Marsh & Svensmark 2000; Carslaw, Harrison & Kirkby 2002). Related, but on much longer timescales, a remarkable correlation has been found between variations in CR, caused by the Solar System's passage through the spiral arms of the Milky Way, and variations in the Earth's climate during the last 1000 million years (Shaviv 2002, 2003; Shaviv & Veizer 2003; de la Fuente Marcos & de la Fuente Marcos 2004; Svensmark 2004, 2006). Recently, a microphysical mechanism has been identified experimentally that links ionization generated from CR secondary particles in the lower part of the Earth's atmosphere and aerosol formation (Svensmark et al. 2006), which may be the fundamental link between cosmic rays, clouds, and climate. In this paper it is shown that the variations of CR and variations in the Earths biosphere represented by fluctuations in the δ^{13}C isotope, covary over almost 4 billion years.

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The paper is organized as follows. First the CR flux at Earth will be determined on the basis of solar evolution and variations in the star formation rate (SFR) in the Milky Way. Then variations in the biological system are obtained from isotope records of δ^{13}C in sediments. Finally a clear relationship between cosmic rays and biological variability is presented and discussed.

2 Cosmic ray history

Before CR can reach the Earth they must penetrate the heliosphere, the region of space dominated by the outflow of magnetized solar wind from the Sun and which presently extends out to a distance of about ≈ 95 AU. The solar wind is capable of modulating the charged flux of CR in the solar system. Solar modulation of cosmic rays reaching the Earth (at 1 AU) is calculated using the steady state, spherically symmetric transport equation, given by

$$V\frac{\partial f}{\partial r} - \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\kappa\frac{\partial f}{\partial r}\right) - \frac{1}{3r^2}\frac{\partial}{\partial r}\left(r^2 V\frac{\partial f}{\partial \ln p}\right) = 0\,, \quad (1)$$

where f is the distribution function of cosmic rays. V is the solar wind velocity, κ is the diffusion constant, p is the momentum of the cosmic ray particles, and r is the radial distance from the center of the heliosphere. The key parameters needed for solving the CR modulation are: 1) the size of the heliosphere $R(t)$ and, 2) the diffusion constant $\kappa(r,P,B)$. Here P is the particle rigidity $P = A/Z\sqrt{T(T+2E_0)}$, A and Z are mass and charge numbers, T is the kinetic energy of the particle, E_0 is the rest energy, and B is the magnetic field strength of the solar wind. 3) Finally the boundary condition for the heliosphere is the Local Interstellar Spectrum (LIS) of CR, as discussed below.

The task is now to determine how the parameters vary as functions of solar evolution and evolution of the LIS.

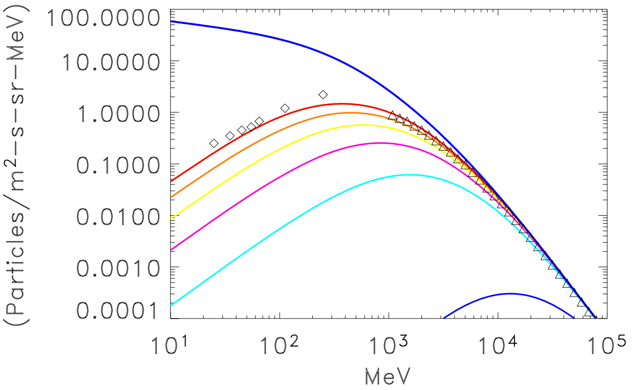

Fig. 1 Differential energy spectrum of cosmic rays at Earth as a function of solar evolution. Red curve ($t = 0$ Gyr), brown ($t = -0.5$ Gyr), yellow ($t = -1.3$ Gyr), purple ($t = -2.1$ Gyr), turquoise ($t = -2.9$ Gyr), and blue ($t = -3.8$ Gyr). Note that the low energies of CR gets depleted. The diamonds and triangles are present day observations, see text.

2.1 Solar evolution

Insight in to the evolution of our Sun is gained from extensive studies of sun-like stars with ages from 100 Myr to 10 Gyr (See for example: Sonnett et al. 1991). The young Sun was rotating at a rate at least 10 times faster than today. As a consequence, the Sun generated vigorous magnetic activity, with coronal X-ray and EUV emissions up to thousand times stronger than today. In addition, the solar wind was denser (Wood et al. 2002). These features indicate that the turbulence in the solar wind was stronger which suggest that the above spherical symmetry of the heliosphere is a good approximation. The radius $R(t)$ of the heliosphere can be found from a pressure balance between the solar wind ram pressure and the pressure of the surrounding ISM. Of interest is the variation of the radius relative to the present radius. We assume $\dot{M}V/R^2 \propto P_{\mathrm{ISM}}$, where $\dot{M}$ is the solar mass loss rate. The relevant ISM pressure is the pressure at the midplane of the Galaxy, which is assumed to be constant. The temporal variation in $R(t)$ therefore becomes

$$R(t) = R(0)\sqrt{\frac{V(t)\dot{M}(t)}{V(0)\dot{M}(0)}}. \qquad (2)$$

The function $V(t)\dot{M}(t)$ has been estimated from solar like stars. The study by Wood et al. (2002) finds a mass loss rate corresponding to

$$V(t)\dot{M}(t) \propto (t)^{-2\pm0.52}, \qquad (3)$$

or to

$$V(t)\dot{M}(t) \propto \exp[-(2.53 \pm 0.51)\sqrt{t}], \qquad (4)$$

where t is time in Gyr. The evolution of the solar wind velocity $V(t)$ is found to vary as (Lammer 2002),

$$V(t) \propto \left(1 + \frac{t}{0.0254\ \mathrm{Gyr}}\right)^{-0.4}. \qquad (5)$$

According to the above the solar wind flux was two billion years ago 2-3 times larger than the present, which is in agreement with paleo solar wind estimates based sputtering of lunar grains (see for example: Sonnett et al. 1991, page 98).

The diffusion constant is related to the characteristic scattering length of the cosmic ray particle as $\kappa(r, P) = c\beta\lambda_c/3$, where λ_c is the scattering length, β is the particle velocity normalized to the speed of light c. A reasonable form of the scattering length is that it is proportional to particle gyro radius, i.e. the rigidity P and the inverse of the magnetic field strength. The magnetic field variation is given by $B_0(r_0/r)^\alpha$, relative to some reference field B_0 at distance r_0, where α is an exponent in the range 0 and 1. For a rotating Parker field, $\alpha \approx 1$,

$$\kappa(r, P, B, t) = \frac{1}{3}c\beta\lambda_0\left(\frac{P}{P_0}\right)\left(\frac{r}{r_0}\right)^\alpha\left(\frac{B_0}{B(t)}\right). \qquad (6)$$

The evolution of the above reference field B_0 in time is assumed to be proportional to the evolution of the solar surface magnetic field (Potgieter 1998) which is related to the solar rotation frequency $\Omega(t)$ as (Ayres 1997; MacGregor & Brenner 1991)

$$B(t) = B(0)\frac{\Omega(t)}{\Omega(0)} = B(0)\left(\frac{t}{4.6\ \mathrm{Gyr}}\right)^{-0.6\pm0.1}. \qquad (7)$$

The above equations relates solar evolution to cosmic ray modulation in the heliosphere.

Using a present day LIS spectrum by Webber & Lockwood (2001) for cosmic ray protons,

$$j_T(R, T, 0) = \mathrm{c}T(T + 2E_0)f(R, T) = \frac{21.1\,T^{-2.8}}{1 + 5.85\,T^{-1.22} + 1.18\,T^{-2.54}}, \qquad (8)$$

as the boundary condition for CR spectrum the effect of solar evolution on the CR spectrum at Earth can be found. Figure 1 shows the influence of only solar evolution on the CR spectrum. The present day spectrum observed at Earth at solar minimum given by the diamonds (McDonald et al. 2001) and triangles (Sanuki et al. 2000) are used to fix the remaining constant in the model, the mean free scattering length (λ_0). In the model the present day solar wind is fixed at $V_0 = 1$ AU/4.34 days. For $\alpha = 1$, $\frac{1}{3}c\lambda_0$ = 0.79 AU^2/4.34 days, and for $\alpha = 1$, $\frac{1}{3}c\lambda_0$ = 79.0 AU^2/4.34 days. Changing the exponent in Eq. (6) between 0 and 1 does only give small qualitative changes to the results. It is therefore stressed that the obtained results are robust. The figures in the following are obtained for $\alpha = 1$.

2.2 Cosmic rays and star formation rate

The remaining information necessary for solving Eq. (1) is how the LIS CR differential spectrum at the boundary of heliosphere has evolved over the history of the solar system. Cosmic rays and Star Formation Rate (SFR) are two processes which are closely related. At any time a small fraction of the formed stars in the Milky Way are so massive that

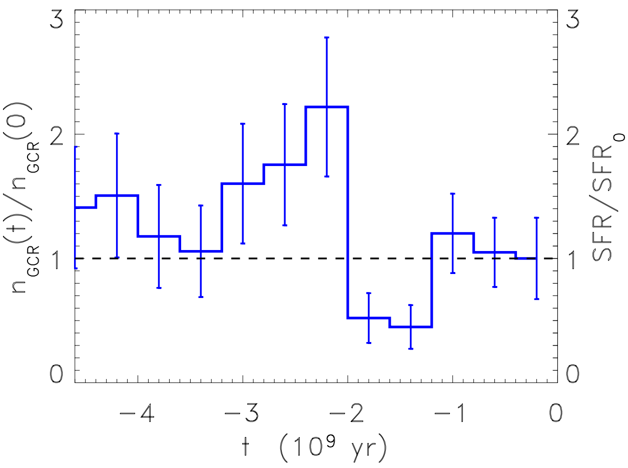

Fig. 2 Histogram of the star formation rate (SFR), adapted from Rocha-Pinto et al. (2000a, 2000b), and the variation in Cosmic Rays (CR) in the Milky Way (see text). Both are normalized to present day values. The temporal resolution is 0.4 Gyr.

they end their lives in a SN. The relevant SN are of type SN II and SN Ib have an initial star of large masse (initial mass 10 times larger than the Sun) and relatively short lifetimes (5–100 Myr, Jørgensen 1997). Variations in the SFR therefore reflect the birth rate of the massive stars, and given their short lifetimes, also the rate of SNs. As SNs are the source of CR, the CR flux in the ISM can be assumed to be proportional to SFR.

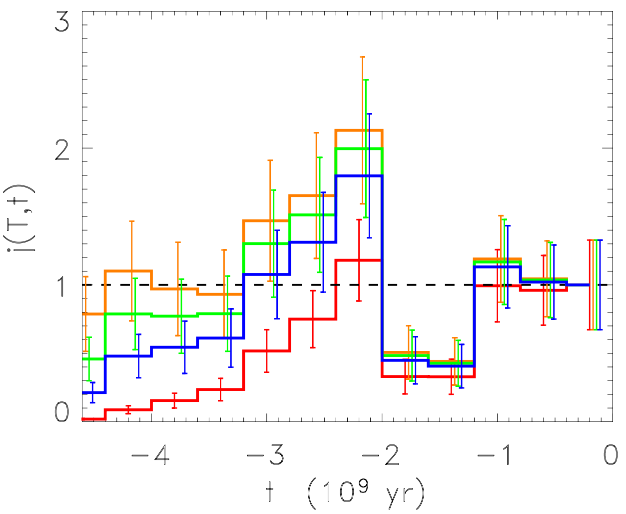

Fig. 3 Variation of CR at 1 AU with energies of 1 GeV (red), 5 GeV (blue), 10 GeV (green) and 20GeV (orange). Note that the higher solar activity of the young sun reduced the heliosphere of cosmic rays. The temporal resolution is 0.4 Gyr.

Figure 2, adapted from a comprehensive study by Rocha-Pinto et al. (2000a, 2000b), shows the SFR history of the Milky Way in time steps of 0.4 Gyr (solid curve), interpreted here as the history of CR intensity variations $n_C R(t)$ in the ISM. The most recent SFR bin -0.4 to 0 Gyr shown, is obtained by disregarding outliers beyond 2σ (Rocha-Pinte et al. 2000a, 2000b), this bin therefore represents stars that have not had time to disperse in the galactic disk. The temporal variation in CR is therefore written

$$j_T(R,T,t) = \left(\frac{\mathrm{SFR}(t)}{\mathrm{SFR}_0}\right) j_T(R,T,0), \qquad (9)$$

where $\mathrm{SFR}(t)/\mathrm{SFR}_0$ is shown in Fig. 2. It is seen that the CR flux and the star-formation rate has been varied over the history of the solar system.

2.3 Cosmic ray variation

Finally the temporal variation of CR at Earth caused by solar evolution and varying interstellar CR flux is estimated, by solving Eq. (1) based on Eqs. (2)–(9). The result is shown in Fig. 3 for CR energies of 5, 10, 20, 30 GeV. Initially the CR flux is suppressed due to the high solar activity. As the activity declines with solar evolution, variations in CR flux begin to reflect variations due to changes in SFR.

The ionization in the Earth's atmosphere below about 35 km is presently almost exclusively caused by CR, of which ionization below 5 km is caused by CR with energies of 10 GeV or more. The exception is ionization by radioactive gases close to the surface over land.

Three billion years ago when the solar output of extreme UV was about 6 times higher (Ribas et al. 2005), free oxygen may have been absent, in which case, there was little or no UV-absorbing ozone. However the Earths atmosphere contained sufficient of other gases, e.g. CO_2 to absorb energetic photons with wavelengths shorter than about 170 nm, making ionization from this source low in the atmosphere highly unlikely (Ribas et al. 2005). Energetic particles accelerated from the Sun only rarely reach the lower part of the atmosphere, and even with a ten-fold increase in the activity of the young Sun, ionization from this source can also be neglected.

The Earth's magnetic field gives some shielding against cosmic rays, and in the course of the Earth's history the magnetic field is estimated to have varied between zero and a factor 2–3 of the present dipole strength. The time scale for variations is of the order of one million years, which is much faster than the 0.4 Gyr time step used in the SFR and CR reconstruction.

Finally the mass of the atmosphere should not have changed considerably ($\approx$ 10 %) since 2.5 billion years ago. Before this time the atmosphere could have contained more mass, leading to an additional screening against cosmic rays.

Under these assumptions Fig. 3 also represents variations in the ionization in the lower part of the Earth's atmosphere through 4.6 billion years, which is assumed to be of interest in connection with climate.

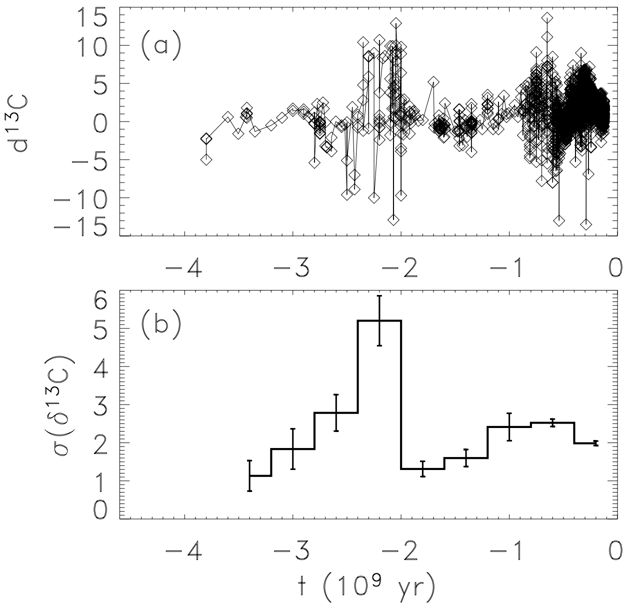

Fig. 4 (a) δ^{13}C record from carbonate sediments over almost 4 billion years. (b) Fluctuations $\sigma(\delta^{13}\mathrm{C})$ averaged over 0.4 Gyr time steps.

3 Cosmic rays and biological productivity

If the varying CR flux has a significant impact on the Earth's climate, signs of the resulting climate variations should be evident in geological records of Earth.

One record reflecting biological conditions is the ^{13}C isotope relative to ^{12}C, (δ^{13}C). Living processes such as photosynthesis discriminate against the heavier ^{13}C isotope, so biological material contains a lower ratio of ^{13}C to ^{12}C than inorganic carbon. This leads to a deficit of ^{13}C in biological material relative to the rest of the carbon reservoirs on Earth, where the fraction of ^{13}C increases. By measuring the carbon fraction δ^{13}C in sediments as a function of time, information relating to the amount of carbon stored in the biosphere, can be obtained. High δ^{13}C in inorganic carbonates implies high productivity in a prosperous biosphere, while low δ^{13}C means a relative scarcity of life.

A remarkable record of δ^{13}C obtained from the Phanerozoic and the Precambrian database of Veizer et al. (1999) and Shields & Veizer (2002), and spanning more than 3 billion years, is shown in Fig. 4 (a). Sometimes the productivity of the biosphere has fluctuated greatly, and at other times it has been more stable. Figure 4 (b) show the size of the fluctuations given by the standard deviation of $x = \delta^{13}$C defined as

$$\sigma(x)_{400} = \sqrt{< (x - < x >_{400})^2 >_{400}} \, . \tag{10}$$

This curve represents variability in the biological system over the past 3 billion years.

Finally, one can compare the CR variations with this biological variability. Figure 5 (bottom panel) shows a comparison between the standard deviation CR at 10 GeV (blue curve) and $\sigma(\delta^{13}\mathrm{C})$ (red curve) over the last 3 billion years. The correlation coefficient between the two records is 0.92 and significant at the 0.9999 level (Monte-Carlo simulation using a normal distribution). In addition an independent study of SFR based on the number and ages of stellar clusters by is also shown (black curve). These data span almost 2 billion years, and are here averaged over the same 0.4 Gyr year intervals as above (de la Fuente Marcos & de la Fuente Marcos 2004).

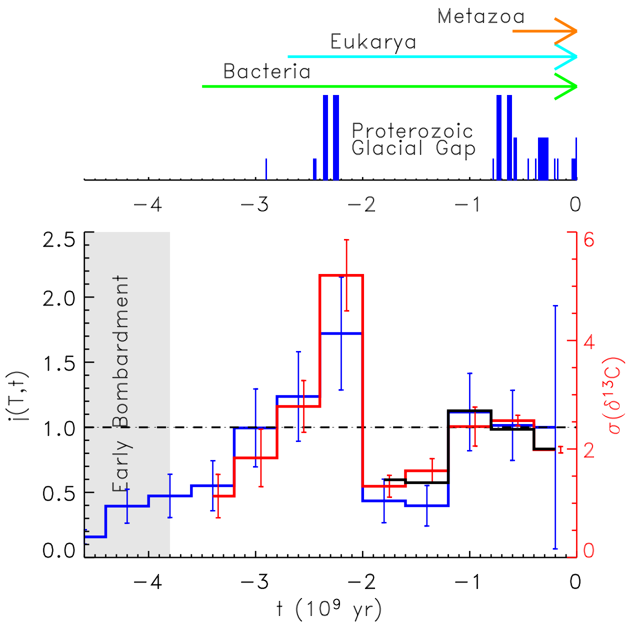

Fig. 5 Upper panel show periods of glaciations (blue bars), and arrows are the temporal extend of major life forms. Bottom panel: CR levels or Standard deviation of CR fluctuations σ_{CR} with energy 10 GeV at 1 AU over 4.6 billion yr (blue curve) and over 2 billion years (black curve). Standard deviation of δ^{13}C fluctuations $\sigma(\delta^{13}\mathrm{C})$ (red curve), all curves in time steps of 0.4 Gyr years (correlation coeff. = 0.92). SFR data based on data from de la Fuente Marcos & de la Fuente Marcos (2004) (black curve). The grey area represent the time when the Earth's was heavily bombarded by asteroids and comets.

In Fig. 5 (top panel) the time-spans of the main life forms are indicated with arrows. Also shown are the periods of glaciations (blue bars) and the height of the bars indicate the severity of the glaciation (Crowell 1999). From the blue curve in the bottom panel, which is the variation of CR flux, over this it is seen that the periods of high CR flux coincide with periods of glaciations, and a 1 billion year glaciation gap coincides with a low CR flux as already noted by Shaviv (2002).

4 Discussion and conclusion

The surprisingly high correlation between CR levels and variability in the biosphere points to a linkage between events in the Milky Way and on the Earth not previously known to geologists and paleontologists. Its meaning is open to discussion. Part of the explanation may be simply that, when the SFR and CR intensities are high, the variations in the CR influx to the Earth, due to its changing position relative to the spiral arms, will be proportionately high as well, thereby implying large fluctuations in the climate.

Moreover the connection between climate and biological productivity can be an inverse relation. During episodes of high CR and cold climate, a large temperature gradient would exist between glaciated sub-polar regions and warm tropics. This would enhance surface winds that stir the oceans and their nutrients vigorously, leading to a *high* biological productivity. This gives the possibility that fluctuations in productivity, can be *large*, with bounds between virtually no biological production and a large production. A warm climate has weak winds, leading to low mixing of ocean nutrients, *low* biological productivity and hence generally *small* fluctuations.

A notable chain of interactions, starting with the star formation rate and solar evolution which via the cosmic rays can influence Earths climate, and subsequently conditions for life, has been identified. If this linkage is confirmed it suggests that the evolution of life on Earth is strongly coupled to the evolution of the Milky Way. The hope is that these results will stimulate cross-disciplinary interest.

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