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Cosmic rays and terrestrial life: A brief review

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ABSTRACT

"The investigation into the possible effects of cosmic rays on living organisms will also offer great interest." – Victor F. Hess, Nobel Lecture, December 12, 1936

High-energy radiation bursts are commonplace in our Universe. From nearby solar flares to distant gamma ray bursts, a variety of physical processes accelerate charged particles to a wide range of energies, which subsequently reach the Earth. Such particles contribute to a number of physical processes occurring in the Earth system. A large fraction of the energy of charged particles gets deposited in the atmosphere, ionizing it, causing changes in its chemistry and affecting the global electric circuit. Remaining secondary particles contribute to the background dose of cosmic rays on the surface and parts of the subsurface region. Life has evolved over the past ~3 billion years in presence of this background radiation, which itself has varied considerably during the period [1–3]. As demonstrated by the Miller–Urey experiment, lightning plays a very important role in the formation of complex organic molecules, which are the building blocks of more complex structures forming life. There is growing evidence of increase in the lightning rate with increasing flux of charged particles. Is there a connection between enhanced rate of cosmic rays and the origin of life? Cosmic ray secondaries are also known to damage DNA and cause mutations, leading to cancer and other diseases. It is now possible to compute radiation doses from secondary particles, in particular muons and neutrons. Have the variations in cosmic ray flux affected the evolution of life on earth? We describe the mechanisms of cosmic rays affecting terrestrial life and review the potential implications of the variation of high-energy astrophysical radiation on the history of life on earth.

1. Introduction

1.1. Background of the possible production sources of cosmic rays: astrophysical sources, fluxes and their probabilities

The Sun is the primary source of radiation on Earth. The total solar irradiance (TSI) is eight orders of magnitude larger in energy flux than cosmic rays. Its photon spectrum peaks in the optical yellow region and the particle spectrum in keV energies. The maximum energy of solar particles is ~MeV except in case of solar flares or CMEs [4], where the energy can reach a few 10 s of GeV [5]. However, in order to have an effect on the biosphere, the radiation should be capable of significantly altering the atmospheric chemistry and/or generating secondary particles so that the radiation dose on the ground is increased significantly.

The geomagnetic field provides a good shield against ~MeV particles, which therefore do not have any significant effect on the biosphere at large. However, since the magnetic field lines guide the charged particles towards the magnetic poles, even low energy particles can impact life in polar regions. Since the flux of galactic cosmic rays (GCRs) is modulated by solar activity, events such as a Forbush decrease (when the solar wind sweeps more galactic cosmic rays away from the Earth) and geomagnetic storms can vary the flux of cosmic rays on short intervals too. Higher energy particles are generated in supernovae shocks, whose estimated rate is about 2–3 per century in our galaxy [6]. A powerful shock accelerates charged particles through the diffusive shock acceleration process. The estimated energy can go up to PeV ranges [7].

1.2. Variation in CR rate: periodic and non-periodic variations

Since charged particles are filtered by the solar and geomagnetic fields, a variation in such fields changes the flux of cosmic rays. A periodic variation in cosmic ray flux is anti-correlated with the solar magnetic field, and is well known as the 11-year solar cycle. The Earth's magnetic field is also known to undergo variations, also known as magnetic field reversals, with apparently total irregularity. However, it has been shown that changes in cosmic ray flux

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due to these reversals are too small to cause any substantial impact on the biosphere [8]. Other minor variations are caused by the periodic lunisolar cycles caused due to the disruption of the Earth–Sun magnetic link by the passage of the moon. Going to longer time periods, the Milankovitch cycles are caused due to the changes in the Earth's orbit around the sun in a periodic manner [9]. It has also been suggested that the Earth may be exposed to a periodic dose of high-energy cosmic rays due to our Galaxy's in fall toward the Virgo cluster coupled with the oscillatory movement of our solar system perpendicular to the galactic plane [10]. This hypothesis predicts an enhanced exposure every ~62 Million years.

Non-periodic variation can occur due to proximity of the Earth with an intense radiation source, such as supernovae [11,12]. Movement of our solar system into a dense interstellar cloud can push back the solar wind plasma, which protects the Earth from GCRs. With little shielding from this plasma, there will be an increase in the rate of Anomalous Cosmic Rays, which can cause severe ozone damage [13]. Large solar proton events occur at a higher rate than nearby supernovae, and can have a moderate impact on the biosphere [14].

2. Mechanisms of CR interaction with the atmosphere

2.1. Ionization and atmospheric electricity

Cosmic ray primaries undergo hadronic interactions upon impact with the atmosphere. The resulting particles either decay or further interact, generating other particles. All charged particles produced in the atmosphere undergo electromagnetic interactions and thus form the 'electromagnetic component' of an air shower. If the energy of the particle is sufficient, it can knock down electrons while traversing through the atmosphere, thereby ionizing it. The location of the peak of atmospheric ionization depends on the primary energy [15]. For the normal GCR spectrum, the peak lies in the stratosphere. Higher energy primaries are capable of penetrating deeper and their peaks are further below, closer towards the Earth.

The mechanism of cosmic ray induced atmospheric ionization's role in generating thunderstorms is not yet established in quantitative terms and research in the field is underway. However the following mechanism is widely agreed upon: Atmospheric electric fields present in thunderclouds are not strong enough to initiate electric breakdown. However, electrons generated by air showers are energetic and can knock down more electrons, creating more ionization, and an electron avalanche is formed. Upon reaching the critical energy, electrons become relativistic runways and result in an abrupt discharge, releasing the energy in form of thunderstorms [16,17]. The value of critical electric field is found to be 1.8 ρ MeV/cm, where ρ is the density in grams per cubic centimeter at a given altitude. This process becomes more efficient with primaries of higher energy as they generate more electrons and deposit more energy in the lower atmosphere. GCRs are also known to modulate the global electrical circuit The concentration of atmospheric ions directly changes with charged particle flux of GCRs and indirectly affects the charges in the troposphere though the modulation of current flow in the global electric circuit [18].

Electric fields of ~10 kV/m are typical in case of thunderstorms. A strong correlation is also observed between cosmic ray intensity and the magnitude of electric field disturbances in some experiments [19]. It must be mentioned that different types of cloud layers produce different types of thunderstorms, which vary in their magnitude and polarity. Both increase and decrease in the intensity in cosmic ray secondaries can thus be observed by experiments depending on the type of event. Work is under progress to get a quantitative understanding of thunderstorms and associated particle acceleration in the atmosphere.

The role of cosmic rays affecting the cloud cover and its impact on the climate [20] has been a topic of intense debate [21]. According to the hypothesis, an increase in comic ray intensity will increase the rate of ionization in the atmosphere and would result in increased cloud formation rate [20]. As the cloud cover would increase, less amount of radiation would reach the Earth's surface and would result in global cooling. Experimental work is underway in CERN to test this hypothesis [22]. If this hypothesis is true, it could explain the early faint young sun paradox. The early Sun is expected to have had ~30% less luminosity compared to the present value and one would expect extremely low temperatures as a result. However, geological records indicate the presence of liquid water on Earth during that era, which contradicts the above statement [23]. This paradox can be partially resolved when one considers cosmic ray flux during that period. Since the sun was more active ~4 Gyr ago, cosmic ray shielding would have been higher from intense solar winds. With lower flux of cosmic rays, the cloud cover is expected to be smaller and would result in 'global warming', thus explaining the paradox [24]. A study also suggested the connection between solar system's crossing of our Galaxy's spiral arm with ice ages due to the increase in cosmic ray activity [25]. However, new calculations with improved map of the Galaxy have disproved this hypothesis [26].

2.2. Ionization and atmospheric chemistry

In the process of cosmic ray induced atmospheric ionization, the triple bond of N_2 and the double bond of O_2 are broken, which results in combination of the two species in a variety of ways and results in changes in atmospheric chemistry [27]. A quantitative estimate of such changes can be made using a photochemical model. It takes on an average 35 eV in the atmosphere to generate an ion pair [28]. Energy deposition by cosmic rays in the atmosphere can be computed using an air shower simulator such as CORSIKA [29], and the number of ion pairs can be computed. Lookup tables are also available which can be used to calculate ion pairs corresponding to the spectrum of any astrophysical source [15,30]. This input can then be used in an atmospheric photochemical model to compute the corresponding changes in atmospheric chemistry.

Changes in atmospheric chemistry have significant implications due to the presence of the ozone layer in the upper atmosphere. The ozone layer is known to block the harmful UVB radiation, which directly interacts with the DNA, causing damage. Here are some representative reactions occurring in the upper atmosphere:

$$NO + O_3 \rightarrow NO_2 + O_2$$

$$NO_2 + O \rightarrow NO + O_2$$

The net reaction is: $O_3 + O \rightarrow O_2 + O_2$

A detailed description of all the reactions can be found elsewhere [31]. However, since high-energy primaries deposit most of their energy lower in the atmosphere, the effect on the ozone layer does not scale directly with the primary energy [27].

Other than ozone depletion and production of ozone at lower altitude, a number of oxides of nitrogen, or NO_x species are also produced. Nitrates can be deposited on the ground through rain and act as fertilizers. This can increase plant growth on short timescales. The main damage due to ozone depletion is by the passage of solar UVB (290–315 nm), which is strongly absorbed by the DNA and protein molecules. This damaging effect is very important, especially for simple organisms such as phytoplankton, which form the base of the food chain and are responsible for half of the World's oxygen production [32]. It can also impact the growth of higher plant life and damage the skin of animals [14].