Long-Term Particle Fluence Distributions and Short-Term Observations

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Abstract

The cosmic environment of Earth directly or indirectly influences conditions for terrestrial life. Cosmic influences include increased fluxes of gas, dust, comets and asteroids, as well as energetic particles and electromagnetic radiation of various energies. The main emphasis of this paper is on the radiation conditions and their variation, together with possible changes in the protective shields or "cocoons" that usually mitigate the dangers of external effects acting on terrestrial life. It is pointed out that the efficiency of protective shields against various kinds of external influences is vastly different, and in some cases their presence may even enhance the detrimental effects. The Sun, the most important pre-condition for terrestrial life, is also discussed as a potential source of danger.

1 Introduction

Terrestrial life has developed and survived in a delicately balanced environment. As no other examples of life-supporting environments have been found so far, it is not known how typical they are in the Universe, and what are the tolerance limits for environmental factors that allow the development and survival of a biosphere. True, some indications are provided by geological records of mass extinctions of species, but records are not complete enough to reliably reconstruct the course of events and to fully establish the cause-and-effect relationship.

Ecological catastrophes may, in some cases, be encoded in the biosphere itself, e.g. in the genes of certain species or in a poorly balanced, unstable mix of interacting species. Another possibility is the sudden or gradual change of environmental factors, to which a substantial fraction of species is unable to adapt. Causes include purely terrestrial effects, such as major tectonic events accompanied by extended volcanism, changes in the inclination of the rotation axis or in the orbit or global magnetic field of the Earth; finally, truly external influences include the impact of gas or particulate matter (such as dust, bolides, comets, asteroids), or large increases of radiation level in the space environment of Earth. Such effects may be due to causes inside the solar system, to the interaction of solar system bodies with passing stars, to changes of the galactic environment along the circumgalactic orbit of the Sun, or to genuine time-dependent events that happen to occur near the solar system (e.g. supernova explosions). Some of those effects will be discussed below, with particular emphasis on radiation effects.

2 Sources of Danger and Protective Shields

A variety of violently active objects are known to exist that would preclude the survival of any life form in their vicinity, due to very high temperatures and/or radiation levels (e.g. quasars, blazars, active galactic nuclei or AGNs, radio galaxies, supernovae and their young remnants, interacting close binary stars, pulsars and magnetars, massive stars). Fortunately, such objects are relatively rare and (at least at present) far away from us. In fact, the best protection against them is distance in the form of the R^{-2} inverse square law, valid for virtually all electromagnetic radiation effects and also, with some modifications, for energetic particle effects. The fact that even the nearest star is more than 10^5 times farther away than our Sun makes the behaviour of the Sun of particular importance.

Terrestrial life is protected against external effects by a variety of shields, such as galactic and heliospheric magnetic fields, the terrestrial magnetosphere and atmosphere. Most shields, however, can also act as guns under certain circumstances. Such is the case for the role of the atmosphere at the impact of very massive bodies that easily punch through the atmosphere. Most of the damage is then done not by the impact itself, but by atmospheric or tidal by-effects, or by delayed climatic effects. The terrestrial magnetosphere, hit by a shock wave propagating in the solar wind, can be distorted to such an extent that while it slowly regains its original form, it also accelerates and pumps a large amount of energetic particles into the inner magnetosphere. Fortunately, the particle energies are – at least according to our present experience – not high enough to endanger life at ground level, although they do endanger spacecraft components and the health and life of astronauts. The turbulence associated with the shock wave surrounding the supersonic solar wind 'bubble' is also a shield against incoming cosmic rays, but at the same time it accelerates ions and creates the anomalous component of energetic interplanetary particles. The distance of that shock wave from the Sun is about 80 to 100 AU, and the accelerated particles do not endanger the biosphere. However, if some external effect pushed that surface much closer to the Sun, an increased flux of more energetic particles might result.

The efficiencies of the shields depend on the nature and energy spectra of the 'shells' fired by the cosmic guns. The most efficient shield against the dangerous components of the present-day space environment is the atmosphere, reducing cosmic ray effects by 2 to 3 orders of magnitude, and solar particle effects even more. Astronauts and high-altitude plane passengers are less shielded. Protection against X and gamma rays is also efficient at sea level and it is insensitive to details of the spectrum of the radiation, while UV protection is mostly provided by ozone, which is much more susceptible to delicate atmospheric radiochemistry. The terrestrial magnetic field protects us by deflecting the majority of the charged particles below certain latitude-dependent energies (except for the polar regions of the magnetosphere). Without that shield (as might be the case at the time of pole reversals), the average surface radiation level would probably increase only by a factor of 2 to 3. Also important is the effect of the heliospheric magnetic field, which reduces ~1 GeV particle flux levels by a factor of 2 to 3, and particles of lower energies even more.

Impacts of big chunks of matter, such as comets and asteroids, are at present rare. However, impact craters and accumulations of cosmic spherules show that in certain periods of the past meteoritic activity was much more intense. Enhanced numbers of comets are expected to visit the inner part of the solar system when a star passing through the outskirts of the heliosphere perturbs the orbits of cometary nuclei 'parked' there. Such stars may be more appropriately considered as 'catapults' than guns. It has been suggested that such events might be responsible for the approximately 30 Myr periodicity of extinctions of species. The most plausible cosmic effect causing such a periodicity is the oscillatory motion of the Sun with respect to the symmetry plane of the galaxy, the half period of which roughly coincides with 30 Myr. The argument is that the density of stars and of other populations (e.g. giant molecular clouds) is higher near the galactic plane, thus perturbations are most frequent when the solar system crosses that plane. It has been pointed out, however, by Bailey et al. (1987), that the distributions around the galactic plane are much too wide to cause such a periodicity with the present oscillation amplitude of the solar orbit. The agreement of the phases is also in doubt.

3 Solar, Heliospheric and Magnetospheric Effects

Solar activity follows a somewhat irregular 11-year cycle. There are indications both for longer cycles and for long quiescent periods (such as the Maunder-minimum from about 1640 to 1710). Most of the solar and interplanetary energetic particles are produced intermittently, either in solar flares or in coronal mass ejections (CMEs) followed by fast interplanetary shocks. In fact, most of the large particle events are due to the latter process (see e.g. Gosling, 1993). Interrelationship among the processes associated with flares and

CMEs have been recently reviewed by Cane (1997). Proton fluxes at MeV energies at 1 AU vary by at least 7 orders of magnitude. With increasing energy, the events become rarer and shorter and the relatively quiet periods longer, but the extreme variability remains.

Both flares and CMEs are products of magnetic reconnection processes, usually occurring in active magnetic field regions of great complexity at or near the Sun. The energy release occurs partly in electromagnetic radiation (e.g. in X-rays), partly in kinetic energy of ejecta, and partly in energetic particles. Each form affects the terrestrial environment differently, but in a crude first approximation they can be compared either on the basis of total energy release in individual 'events', or in terms of 'peak' fluxes measured at the boundary of the terrestrial magnetosphere.

More than 20 years ago, Wdowczyk and Wolfendale (1977) addressed the question of the long-term frequency of large solar energy releases and their possible effects, compared with other catastrophic events. The main body of their evidence appears still valid, although some details have changed.

The very flat integral power-law fits (logarithmic slope around -0.5) suggest that several dramatic solar energy releases should be expected in geologically short times, if the trend continues. One has to take into account, however, that events with low energy-fluences are identified less efficiently, and that the slope might steepen with increasing fluence (energy-fluence is the energy-flux integrated over the duration of an event). The long-term extrapolation depends critically on the functional form chosen. One possibility is the log-normal model of Feynman et al. (1993), which has been widely used for short-term risk analysis of manned and unmanned space missions. They based their interplanetary fluence engineering model 'JPL 1991' on IMP and OGO fluence data measured between 1963 and 1991 for proton fluences above five limiting energies. Extrapolating their highest energy (>60 MeV) fit to long time-scales, it turns out that while the highest fluence measured up to now (in about 25 years) was $3\ 10^{9}$ cm^{-2}, one would expect in 1 Myr a few events above 10^{12} cm^{-2}, and in 100 Myr a few above 10^{13} cm^{-2}. This is far less than one would expect from the flat slopes found by Wdowczyk and Wolfendale (1977), but probably more realistic. Thus the largest solar particle fluences in geological history should have been not more than 10^{3} to 10^{4} times larger than those detected so far, giving rise to only moderate 'energetic particle catastrophes'. One might suspect that the time dependence in the efficiency of the magnetospheric protective shield considerably enhances the dangers. This might be the case if the fluence distribution decreases very fast on the high end (faster than the log-normal fit). If, however, the decrease is consistent with the above model, then the probably much shorter periods when the strength of the magnetosphere is anomalously low, do not allow sufficiently large particle enhancements to occur with high enough probability.

Somewhat higher radiation effects might be inferred if hard X-ray data are used. As X-rays propagate in straight lines, flare-type events can be seen from a whole hemisphere of the Sun. The frequency distribution of peak counting rates of over 7000 solar hard X-ray flares was compiled and discussed by Dennis (1985). A differential power-law spectrum with exponent -1.8 was obtained over more than 3 orders of magnitude (corresponding to an integral exponent of -0.8). Such a spectrum is in excellent agreement with predictions of self-organized 'avalanche' or 'sand-pile' models (Lu and Hamilton, 1991). The idea is that solar active regions are in a critical state like a sandpile with critical slopes so that the addition of a single sand-grain might initiate an avalanche of virtually any size, and energy releases follow a power-law distribution. In fact, simulations show that the power-law exponent of -1.8 for peak rates of energy releases is feasible, and the same mechanism would give -1.4 for exponents of total energy releases in individual avalanches (the time lengths of avalanches for given energy releases can also be inferred). The upper limit of energy releases of course depends on the size of the 'sandpile', and that is not easily inferred for solar processes. Avalanche-type processes also occur in the terrestrial magnetotail and magnetosphere, and their limiting magnitude is also unknown.

4 Cosmic Rays and Supernovae

A supernova explosion should occur very rarely close enough to Earth (e.g. once in about 10^8 years at a distance of 10 pc or less) to have a substantial effect on terrestrial life. A prompt optical and UV flash would increase atmospheric ionization even from larger distances, but that first flash is unlikely to cause a lasting effect. X and gamma radiation, arriving somewhat later, would be mostly absorbed in the atmosphere, and very little would penetrate to ground level. Although very energetic cosmic rays might arrive within a few years after the light-flash, their energy content would be small, and an important effect on life is unlikely. The main component of cosmic rays would arrive thousands or tens of thousands of years later, probably together with the shock. The shock might push back the solar wind and set Earth more open for direct effects, but the atmosphere would still effectively protect life against direct radiation increases – even if cosmic ray fluxes at ground level increased by a factor of ten or so for a few hundred or thousand years. Indirect effects through atmospheric chemistry and ozone destruction, followed by some ecological chain reactions, might be more important. Very large fluctuations in solar activity, mainly if combined with a reduction of terrestrial magnetic field, might perhaps give an equally or even more plausible explanation for some of the mass extinctions (Wdowczyk and Wolfendale, 1977). However, as suggested e.g. by Clark et al. (1977), the supernova scenario is certainly one of the possibilities. A recent, detailed discussion of the expansion of the supernova ejecta and shock, and possible isotopic signatures in terrestrial geological archives was given by Ellis et al. (1886). One important point is that supernova explosions might contribute not only radiation and energetic particles, but also to dust grains, which may or may not survive atmospheric entry. If they do and are preserved as spherules, their isotopic composition might be checked for supernova signatures.

Apart from supernovae of the distant past, a search for recent nearby supernovae is also of considerable interest. Cosmic rays might hold the key for such discoveries. Although at present cosmic rays are surprisingly isotropic and their energy spectra are smooth up to about 10^{14} eV, some increase of anisotropies and a rather peculiar spectral behaviour is experienced in the spectral 'knee' region at above 10^{15} eV, where the spectrum becomes steeper. Erlykin and Wolfendale (1998) have analyzed the situation, and found some evidence for a substantial single-supernova contribution over and above the smooth background due to a large number of earlier and more distant supernovae.

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