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Cosmogenic element production in meteorites – the influence of long-term variation in heliospheric structure

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Abstract. The heliosphere is identified as an important shield against interstellar hazards caused by cosmic rays and neutral atoms. It is demonstrated by quantitative modelling that a change of the interstellar medium surrounding the heliosphere, as a result of the Sun's quasi-Keplerian motion around the galactic center, can trigger significant changes of planetary environments due to enhanced fluxes of both neutral atoms and cosmic rays. Such enhanced cosmic ray fluxes should also have an influence on the production of cosmogenic elements in meteorites. Here we investigate the influence of increased cosmic ray fluxes on the build-up of cosmogenic isotope anomalies in meteorites during their migration from the outer heliosphere to the Earth. Probable candidates for influencing isotopic anomalies are anomalous cosmic ray particles in the energy range between 1 to 100 MeV/nucleon which attain their highest flux levels in the region close to the solar wind termination shock. We present first results.

1 Introduction

The heliosphere, i.e. the plasma bubble formed by the solar wind around the Sun, shields the planets from a direct irradiation with both energetic interstellar particles (galactic cosmic rays, GCRs) and particles energized in the boundary region of the heliosphere (anomalous cosmic rays, ACRs). Also the flux of interstellar neutral atoms at the orbits of the terrestrial planets is significantly reduced due to a filtration in the heliospheric interface and the (photo- and charge exchange-) ionisation upon approaching the inner heliosphere.

Due to the orbit of the Sun around the galactic center the interstellar environment at the boundary of the heliosphere is changing, implying changes in the structure and extension of the heliosphere as well as in the intensity of the cosmic rays (CRs) and neutral gas fluxes. On the one hand, the neutral gas component of the local interstellar medium (LISM) flows almost unhindered into the heliosphere and, in case of sufficiently high fluxes, can change the chemistry of planetary atmospheres. On the other hand, significant fractions of GCRs from the LISM and the ACRs produced in the outer heliosphere reach the environments and surfaces of the terrestrial planets, moons, asteroids and meteoroids. Besides an influence on planetary magnetospheres (e.g., via current systems) and atmospheres (e.g., via cloud formation), there is a production of radioactive elements due to the direct imprints in the surfaces of celestial bodies. These so-called cosmogenic elements serve as clocks providing information about the past of the solar system. Thus, the surfaces of such Earth-like celestial bodies (terrestrial bodies) can be considered as 'cosmochronic' archives, see, e.g. Schweingruber and Bochsler (2000). The legibility and reliability of these cosmochronic archives depends on the knowledge of the production rates of cosmogenic elements, i.e. on the corpuscular irradiation history of the surfaces and, thus, depends on the intensity of the CR flux in the past. This intensity is determined by the structure of the heliosphere because both the interstellar spectra of GCRs and the source spectra of ACRs are modulated by heliospheric transport processes.

In the following we discuss the changes in the heliospheric structure due to changes in the LISM, the consquences for the CR intensities and, in turn, for the radiation history of meteoroids.

2 The LISM and the structure of the heliosphere

A change in the basic structure of the heliosphere induced by a changing interstellar environment has already been discussed in the 1970's (Begelman and Rees, 1975). According to these studies, the entry of the Sun and the heliosphere into a dense interstellar cloud ($n \sim 10^2 - 10^3$ cm^{-3}) could cause the heliospheric shock to be pushed in the region inside the Earth orbit, so that the Earth would be located in the heliospheric interface. The orbits of the outer planets could even lie beyond the heliopause. The consequences for planetary environments would be (i) a major change in atmospheric

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chemistry due to the direct contact with the LISM, (ii) a significantly increased CR intensity, and (iii) a separation of the planetary magnetospheres from the heliospheric magnetic field (for potential implications see Scherer (2000)).

For a long period, the investigation of a varying heliospheric structure was carried out on a qualitative level only, and the first quantitative studies were exclusively concerned with variations of the heliospheric structure due to the solar activity cycle. Only recently, multidimensional models have made possible quantitative analyses of the time-dependent influence of the LISM. Zank and Frisch (1999) have studied the effect of a denser LISM in detail. Nonetheless, their discussion of the implications of higher neutral gas fluxes remains qualitative, and the effect of an altered CR intensity was not taken into account. An extension to more consistent multifluid models specifically including the presence and influence of ACRs was achieved by Fahr, Kausch and Scherer (2000) and a qualitative investigation of the effect of CRs can be found in Scherer (2000) and Scherer et al. (2001).

A typical result of such modelling for the large–scale structure of the heliosphere is shown in the upper panel of Fig. 1 showing the proton number density in the rest frame of the Sun, in which its motion relative to the LISM appears as an interstellar wind (blowing from right to left). Both the solar and interstellar wind undergo shock transitions: the heliospheric shock (inner closed solid line) and the bow shock (outer open solid line), respectively. The two plasmas are separated by a contact discontinuity, the heliopause (solid line between the two shocks). Typical heliocentric distances in the direction upwind with respect to the interstellar flow for the present situation, as resulting from the models, are 80–100 AU for the heliospheric shock, 150–200 AU for the heliopause and 300–400 AU for the bow shock. Currently, the local interstellar cloud is believed to be characterized by a proton density of $n_p \approx 0.1$ cm^{-3}, a hydrogen atom density of $n_H \approx 0.1$ cm^{-3}, a temperature of $T \approx 8000$ K, a speed of $v \approx 25$ km s^{-1}, a magnetic field strength of ~1.4 μG and a CR energy density of ~0.5–1 eVcm^{-3}.

As mentioned above, the LISM properties change due to the motion of the Sun within the Galaxy. For the structure and especially the extent of the heliosphere the total pressure of the LISM is the most important parameter. The total pressure comprises the pressures of the thermal plasma, the CRs, and the magnetic field. While all of those can differ in distinct galactic regions along the solar path, the change in thermal plasma pressure is, supposedly, the strongest. At the time when the Sun was traversing the Local Bubble, the thermal plasma pressure $P_{th} = 2nkT$ outside the heliosphere was $P_{th} \approx 0.015$ eVcm^{-3}, compared to $P_{th} \approx 0.3$ eVcm^{-3} presently in the local interstellar cloud. The number density of the LISM can easily exceed the present value by one or two orders of magnitude without implying a compensating decrease in temperature, so that the external pressure could be higher by a factor of 10 or 100.

The principal effect of a higher LISM pressure on the structure and extension of the heliosphere has been explored by Zank and Frisch (1999). These authors used a model neglecting the effect of CRs on heliospheric structure but discussed the principal effect of an enhanced CR flux on the production rate of cosmogenic elements (^{10}Be). Then, Scherer (2000) and Scherer et al. (2001) employed the model by Fahr, Kausch and Scherer (2000) that self-consistently includes the dynamical influence of CRs in order to improve the study of the shielding efficiency of the heliosphere w.r.t. to CRs. Additionally, they discussed the consequences of an increased CR flux on the environment of Earth. To avoid extremes they considered a situation in which the heliosphere is immersed in an interstellar cloud ten times denser than presently. Assuming that the only change in outer boundary conditions is indeed that of the number density (thereby, for simplicity, excluding a change in the ionisation degree), the model yields the heliospheric configuration depicted in the lower panel of Fig. 1. Obviously, the heliospheric extent is much reduced: the heliospheric shock in upwind direction is located at ~35 AU, the heliopause at ~60 AU and the bow shock at ~80 AU. So, a number density increase by a factor of ten results in a shrinkage of the heliosphere by about a factor of three.

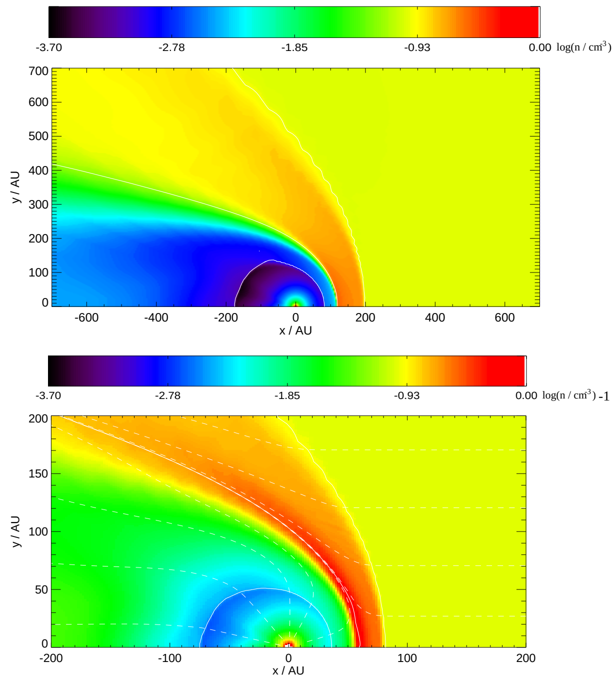

Fig. 1. The structure of the heliosphere resulting from an axisymmetric model (Fahr, Kausch and Scherer, 2000): the proton number density seen in the rest frame of the Sun for a proton and neutral gas number density of the local interstellar medium of $n_p = n_H = 0.1$ cm^{-3} (upper panel) and $n_p = n_H = 1.0$ cm^{-3} (lower panel). The innermost solid line indicates the position of the heliospheric shock, the middle line the heliopause, a contact discontinuity separating the stellar from the interstellar plasma, and the outermost line a bow shock at which the interstellar plasma flow decelerates to subsonic speed. The dashed lines in the lower panel indicate the streamlines of the plasma flow. Note, that the two plots have different scalings and grey-scale codings.

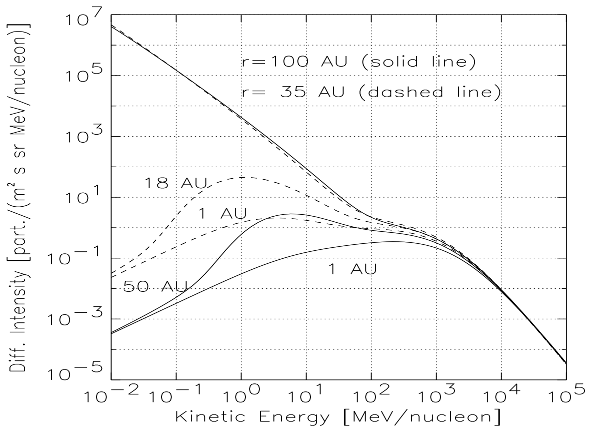

Fig. 2. Cosmic ray modulation in the heliosphere: present–day results for the differential intensities of CRs for a heliospheric termination shock at 100 AU (solid lines) and for a fictitious heliosphere with a shock at 35 AU (dashed lines). The solar wind speed is 400 km s^{-1} in both cases. From top to bottom, the solid lines denote the CR proton spectrum at 100 AU (present boundary), 50 and 1 AU and the dashed lines those at 35 AU (boundary of shrinked heliosphere), 18 and 1 AU. The boundary spectrum is, at energies below ∼100 MeV, determined by ACRs accelerated at the heliospheric shock. At higher energies it is dominated by GCRs (see Scherer, 2000).

3 Consequences for the cosmic ray flux

In general, the interstellar fluxes of CRs are reduced within the heliosphere, mainly inside the heliospheric shock which, according to current understanding, is representing the main modulation boundary for CRs. However, modulation models based on this equation are just at the beginning to include realistic heliospheric configurations, see, e.g. Fichtner (2001). It is, therefore, difficult to predict on the basis of such models the CR flux when the heliospheric shock is closer to the Sun and, thus, the main modulation region is reduced. Because the solar wind flow and the heliospheric magnetic field structure inside the shock surface might be significantly changed, the heliospheric structure as a whole is modified and the CR modulation might be very different from what is observed nowadays.

In order to get a basic idea of the CR flux at 1 AU a semi–analytical solution of the CR transport equation can be employed, for details see Stawicki et al. (2000). While the assumed spherical symmetry of the solution limits its applicability to regions close to a given direction, here the upwind direction, it allows one, to estimate the basic change in the CR flux levels. A first effect of a reduced heliocentric distance of the heliospheric shock (with all other parameters unchanged) is illustrated in Fig. 2 giving the modulated spectra of CRs approximately expected for the two heliospheric structures shown in Fig. 1. Obviously, the CR flux at Earth is significantly increased for a smaller modulation region: it is ∼ 10 – 100 times higher for kinetic energies below 100 MeV and 2 – 3 times in the interval 0.1–1 GeV. A second effect (not shown in the figure) is a lower solar wind speed, say

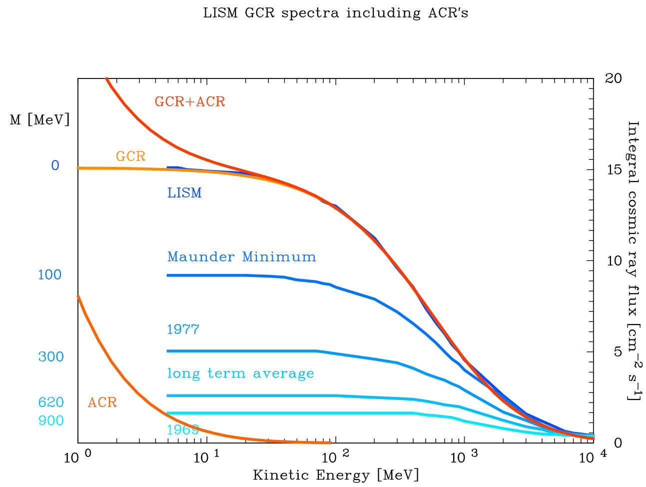

Fig. 3. The integrated GCR spectra in the (present) LISM (uppermost line), during a solar activity minimum (1977) and maximum (1969), during the Maunder minimum, and for the long-term average. The ACR contribution is shown separately. The modulation parameter (see text) is given on the left vertical axis.

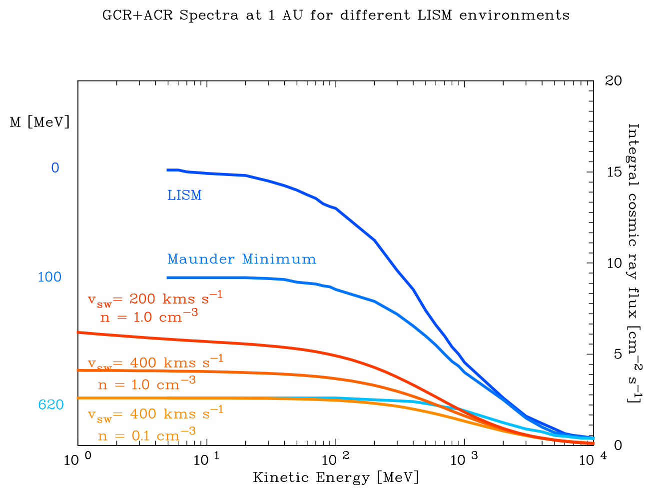

Fig. 4. Same as Fig. 3, but with the integrated CR spectra for the case of a modifeid heliosphere. The present-day case is set equal to the long-term average of Fig. 3.

200 km s^{-1} at the heliospheric shock. Then the convection of CRs in anti–solar direction is reduced, and the flux levels are further increased by factor of two above 0.1 GeV and up to 1000 below 0.1 GeV. Therefore, combining both effects one obtains for the energy range 0.1–1 GeV a CR flux increase at Earth by a factor of about six. This energy interval is most interesting, because these CRs penetrate the Earth's magnetosphere and reach the atmosphere or even ground level. A possible relation between the CR flux and cloud formation has been discussed by Svensmark (1998).

4 Consequences for the irradiation history of meteoroids

The evolutionary history of meteoroids/meteorites, their residence time in interplanetary space and on Earth can be explored by a determination of the abundances of different isotopes. A common basic assumption for this dating method is an anti-correlation of the CR flux (here only GCRs) with only the quasi-periodical changes in the solar activity (Michel and Neumann, 1998; Leya et al., 2000). Usually, a modulation parameter is derived from the spectrum of the GCRs. This parameter can either be interpreted as a characteristic energy determining the shape of the modulated spectra, or, for sufficiently energetic particles, as the energy loss on their way from the modulation boundary (the heliopause or the heliospheric shock) to a given heliocentric distance (Michel and Neumann, 1998). It varies with the solar cycle between 300 MeV (solar minimum) and 900 MeV (solar maximum), with a minimum value of 100 MeV during the so-called Maunder Minimum (which lasted from ca. 1645 to 1715). Typical (integrated) CR spectra as used by, e.g., Michel and Neumann (1998) are displayed in Fig. 3.

With the knowledge of this modulation parameter the production rates of cosmogenic elements in meteoroids/meteorites can be determined. The solar activity causing a variation in the CR flux and hence in the modulation parameter results in a change in the production rate of, e.g., ^{44}Ti by a factor 1.8 (Michel and Neumann, 1998). Also the production rate of ^{14}C during the Maunder Minimum was enhanced by a factor of 2 (Beer, 2000) compared to that at present time, which was possibly caused by a factor of 2 lower solar magnetic field strength (Solanki et al., 2000). In Fig. 4 the integrated CR spectra in a heliosphere that is modified as discussed in connection to Figs. 1 and 2 are compared to those derived for typical solar activity minimum and maximum conditions. Including both the effect of a smaller modulation region and that of a less efficient outward convection increases the CR flux by about a factor of 2. Given that the duration of such flux increases due to a changing heliospheric structure is much longer than that of solar activity or even the Maunder Minimum, they should be taken into account into studies based on the long-term data to explain the cosmogenic element abundances in meteoroids/meteorites.

In addition, some of the cross sections for the production of cosmogenic elements exhibit a maximum in the energy interval 10 to 100 MeV (for examples see Fig. 5). Consequently, one has to expect an additional production of such elements in meteoroids due to their irradiation with ACRs the effect of which has not yet been included into corresponding studies.

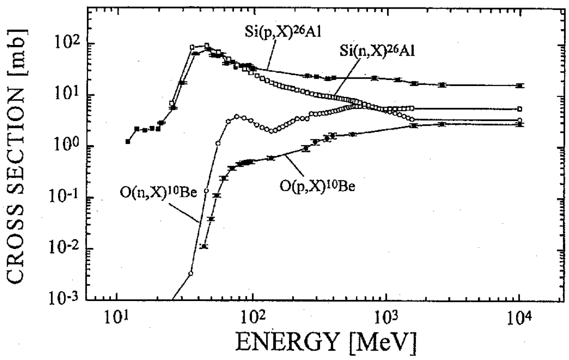

Fig. 5. Proton and neutron cross sections for the production of the cosmogenic elements ^{1}0Be and ^{2}6Al from O and SI, respectively. Taken from Leya et al. (2000).

5 Discussion

Changes of the cosmic ray flux resulting from changes in the structure of the heliosphere which, as consequences of a changed LISM condition, may easily last 10^6 years or longer, and can be much more important than, e.g., those during short-term (∼11-years) and intermediate-term (like the Maunder minimum) periods. So, for a long time, the production of cosmogenic elements in meteoroids/meteorites may have been much higher or smaller than the present (solar cycle-averaged) value. Therefore, emphasis should be put on this aspect regarding interpretations of the abundances of these elements in the context of cosmochronic archives.

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