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History of the solar environment

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Abstract. Galactic cosmic rays (GCR) provide information on the solar neighborhood during the sun's motion in the galaxy. There is now considerable evidence for GCR acceleration by shock waves of supernova in active star-forming regions (OB associations) in the galactic spiral arms. During times of passage into star-forming regions increases in the GCR-flux are expected. Recent data from the Spitzer Space Telescope (SST) are shedding light on the structure of the Milky Way and of its star-forming-regions in spiral arms. Records of flux variations may be found in solar system detectors, and iron meteorites with GCR-exposure times of several hundred million years have long been considered to be potential detectors (Voshage, 1962). Variable concentration ratios of GCR-produced stable and radioactive nuclides, with varying half-lives and therefore integration times, were reported by Lavielle *et al.* (1999), indicating a recent 38% GCR-flux increase. Potential flux recorders consisting of different pairs of nuclides can measure average fluxes over different time scales (Lavielle *et al.*, 2007; Mathew and Marti, 2008). Specific characteristics of two pairs of recorders (^{81}Kr-Kr and ^{129}I-^{129}Xe) are the properties of self-correction for GCR-shielding (flux variability within meteorites of varying sizes). The ^{81}Kr-Kr method (Marti, 1967) is based on Kr isotope ratios, while stable ^{129}Xe is the decay product of the radionuclide ^{129}I, which is produced by secondary neutron reactions on Te in troilites of iron meteorites. The two chronometers provide records of the average GCR flux over 1 and 100 million year time scales, respectively.

Keywords. Galactic cosmic ray (GCR) flux, Starforming regions in galaxy, Chronometers for GCR flux calibration, Iron meteorites as flux recorders

1. Introduction

Galactic cosmic rays (GCR) provide information on the energy density and on the discrete sources in the "local" region of the galaxy. The energies of GCR (typically 100 MeV to 10 GeV) probably derive from supernova (SN) explosions, which occur once every 30 to 60a in the galaxy (e.g. Axford, 1981). In order to maintain the currently observed intensity of GCR over millions of years, only a few percent of the SN energy has to be used for the GCR acceleration. There is considerable evidence that this acceleration is accomplished in the shock waves as they propagate through the surrounding interstellar gas. This GCR origin is not only suggested from direct observational evidence, but is based on the recognition that the predominant types of SN in spiral galaxies like our own are those which originate from massive stars, predominantly in spiral arms where most massive stars are born and die (Dragicevich *et al.* 1999). The recent Spitzer (SST, NASA, 2008) data provide a considerably different structure of the spiral arms in our own galaxy. High contrasts in the non-thermal radio emission are observed between the spiral arms and the disks of spiral galaxies. Whenever our Sun was located in a region of the galactic spiral arms which show star formation regions (OB associations), an increased GCR flux has to be expected.

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The GCR flux and the path lengths of GCR reaching the solar system are also affected by the interstellar medium (ISM). Begelman and Rees (1976) calculated that while crossing moderately dense ISM clouds with densities of 10^2 to 10^3 atoms cm^{-3}, the bow shock of the heliosphere will be pushed inward further than 1 AU. As a consequence, the GCR slowing down effect by the heliosphere will cease to work and the flux of lower energy particles will be significantly increased. It has also been speculated (e.g. Shaviv 2002, 2003) that variable GCR fluxes may be connected to the Earth's cloud cover and possibly the appearance of ice ages.

The position of our Sun with regard to the star formation regions (the original OB associations have lost their O-members, because these have already ended their cycles as SNe), has been investigated in several surveys. The SST measurements of the spiral structure, and in particular the number of arms, has changed and these data suggest that the picture of two major arms is more favorable than for four. They appear to govern the flux systematics for the Sun's orbit in the Milky Way. Direct evidence for recent close-by events is not strong, but Knie *et al.* (2004) report ^{60}Fe in a deep-sea manganese crust as evidence for a supernova 2.8 Ma ago. A comprehensive census of the stellar content of the OB associations within 1 kps from the Sun was reported by De Zeeuw *et al.* (1999). This is a project which studies the formation, structure, and evolution of nearby young stellar groups and related star-forming regions. The OB associations are unbound moving groups which can be detected kinematically because of their small internal velocity dispersion.

In general, the intrinsic flux of cosmic rays reaching the outskirts of the solar system is proportional to the star formation rate in the solar system's vicinity. Although there is a lag of several million years between the birth and death of the massive stars which is ultimately responsible for cosmic ray acceleration, this lag may be small when compared with the relevant time scale of GCR flux variations during the last $\sim$ 100 Ma. In order to investigate the effects of the spatial and temporal variations and of clusterings of cosmic-ray sources, Higdon and Lingenfelter (2003) developed a model to calculate the age and path length distributions of cosmic rays reaching the solar system by summation of the diffusive contributions of known discrete sources. This model calculation includes the galactic star-forming regions and the OB stars lost subsequently as SN. In principle, this allows the separation of effects due to spatial and temporal clusterings in the solar neighborhood on the local GCR flux variations.

Direct measurements appear possible and require measurements of GCR flux changes and production rate calibrations, based on the systematics of GCR-produced nuclides in iron meteorites. A variability may be inferred from differences in calculated average-fluxes based on cosmic-ray-produced radionuclides of 0.2 to 16 Ma half-lives, as well as associated stable decay product nuclides, which integrate over the time of exposure of these natural monitors. We address some of these efforts and recent experimental progress. In analyzing such GCR flux monitors data, one can first show that the use of constant production rates leads to contradictions in CRE ages, and then evaluate flux models which yield consistent CRE ages and select those which are consistent with dynamic models for the clustering of cosmic ray sources and inferred temporal variations.

2. Development of GCR Flux Monitors

It has long been recognized that iron meteorites are excellent fossil detectors of cosmic rays since some of them were exposed for periods in excess of 1 Ga. A substantial database of cosmic-ray-produced nuclides already exists, including the data from the ^{40}K/^{41}K method, first developed by Voshage (1962). Several studies indicated systematic

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differences between ages obtained by radioactive and stable nuclide pairs, such as ^{36}Cl/^{36}Ar, ^{39}Ar/^{38}Ar, and ^{10}Be/^{21}Ne when compared to the ^{40}K/^{41}K results. Although several authors interpreted this as evidence for variability in the cosmic ray flux, the data from several iron meteorites also indicated complex exposure histories. Complexities were also found in spallation records from different locations within the same meteorites, specifically for large recovered masses. In many cases the evidence for complex exposure histories in iron meteorites was difficult to assess, but cosmic-ray records in iron meteorites must take into account evidence for multiple breakups in the evaluation of possible variations in cosmic-ray intensity. A combined study of complex exposure histories and of the constancy of galactic cosmic rays was carried out by Lavielle *et al.* (1999). The authors' goal was to recalibrate the ^{40}K/^{41}K ages for a large number of iron meteorites which were inferred to have experienced simple exposure histories.

In this flux calibration the authors assumed a time-independent cosmic ray flux for a 0.5 Ga period. Their results show that average fluxes based on the ^{40}K halflife (1.26 Ga) disagree in a systematic way with calibrations based on radionuclides of about million year half-lives (^{81}Kr, ^{36}Cl, ^{10}Be, ^{53}Mn). Their calculated average production rates of ^{36}Cl or of ^{36}Ar over the calibration interval (0.15-0.70 Ga) were lower by 28%, when compared to production rates commonly used for the recent cosmic-ray flux. These authors concluded that a recent cosmic ray flux increase offered a most straightforward explanation, but they cautioned that uncertainties in spallation systematics for product nuclei close to a doubly magic mass number (40) should not be ignored. They further concluded that the magnitude of the resulting shifts in exposure ages depend on adopted models for flux changes. The recent GCR flux increase inferred by Lavielle *et al.* (1999) compared to average fluxes during the time interval 150 to 700 Ma ago did not provide specific information about the timing of the increase, nor the possibility of a cyclic variation. The geometries and crossings into spiral arms of our galaxy need to be reevaluated based on the new SST data.

3. Shielding-correcting nuclide pairs

1. Flux monitors for the past 1 Ma

Two chronometers are useful for the determination of the recent GCR flux: ^{81}Kr - ^{83}Kr$_c$ ($t_{1/2} = 0.23$ Ma), and ^{36}Cl - ^{36}Ar ($t_{1/2} = 0.30$ Ma).

These chronometers are ^{81}Kr – ^{83}Kr$_c$ ($\lambda_{81} = 3.24 \text{ x } 10^{-5}$ a^{-1}) with ^{81}Kr(t) = (P$_{81}$/λ_{81}) (1 – exp(-λ_{81} t)) and a measured ratio [^{83}Kr$_c$] / [^{81}Kr] = (P$_{83}$/P$_{81}$) λ_{81} T$_{CRE}$/(1 – exp (-λ_{81} T$_{CRE}$)) and the chronometer ^{36}Cl – ^{36}Ar$_c$ ($\lambda_{36} = 2.46 \times 10^{-5}$ a^{-1}) with ^{36}Cl(t) = (P (^{36}Cl)/λ_{36}) (1 – exp(-λ_{36} t)) and measured [^{36}Ar$_c$]/[^{36}Cl] = P$_{36}$(^{36}Ar)/P$_{36}$(^{36}Cl) λ_{36} T$_{CRE}$/(1 – exp (-λ_{36} T$_{CRE}$)) which in both cases self-correct for GCR-shielding variations (assuming a single exposure geometry).

They are expected to give identical CRE ages of iron meteorites, and can be used for cross-calibrations, as long as the recent flux was constant. The first chronometer (Marti, 1967) has been considered to be one of the most reliable methods for cosmic-ray-exposure dating. Concentrations of the radionuclide ^{81}Kr in meteorites are typically of the order of several 10^5 atoms per g of sample, but are considerably lower in large iron meteorites. This limitation required the development of a new mass spectrometer with very high sensitivity. Such a facility has been developed at CNAB (University of Bordeaux), making use of resonant laser ionization (RIS) for Kr at 216.4 nm, using cryogenic sample concentrator and a time-of-flight mass analyzer (Lavielle *et al.*, 2007). This technique is about 50 times more sensitive than a conventional mass spectrometer

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and achieves a mass resolution of about 400 and a detection limit for ^{81}Kr $\leqslant$ 1,000 atoms (Lavielle *et al.*, 2007); first results have been obtained for iron meteorite Old Woman.

2. Flux monitors during the past 10 Ma

The pairs ^{10}Be – ^{21}Ne ($t_{1/2}$ = 1.6 Ma) and ^{53}Mn – ^{53}Cr ($t_{1/2}$ = 3.7 Ma) are largely self-correcting for shielding variability and are considered to represent suitable monitors for the last 10 Ma. The radionuclides (by AMS) and integrating stable spallation components (^{53}Cr the decay product) need to be measured.

3. Flux monitor during the past ∼100 Ma

The chronometer ^{129}I – ^{129}Xe$_c$ (λ_{129} = 4.6 × 10^{-7} a^{-1}) with ^{129}I (t) = P_{129}/λ_{129} [1 – exp (-λ_{129}t)] and a ratio [^{129}Xe$_n$]/[^{129}I] = λ_{129} T_{CRE} / [1 – exp (-λ_{129} T_{CRE})]$^{-1}$ is suitable to study a possible recent (<100 Ma) flux increase.

This change is assessed by the nuclide of appropriate half-life, ^{129}I which is produced by neutron reactions on Te. This $t_{1/2}$ = 16 Ma is ideal for monitoring changes in the GCR flux over the last 100 Ma. The ^{129}I-^{129}Xe$_n$ chronometer (Marti, 1986) which is based on the pair ^{129}I and its integrating stable decay product ^{129}Xe was used in a study of troilite in Cape York (Murty and Marti, 1987). However, the cosmic-ray-produced ^{129}Xe$_n$ needs to be resolved from products of “extinct” ^{129}I. The presence of a GCR spallation component is observed by elevated ^{124}Xe/^{130}Xe and^{126}Xe/^{130}Xe ratios, compared to corresponding ratios in the trapped Xe component. In iron meteorites products due to low energy neutron capture reactions on ^{127}I, ^{128}Te and ^{130}Te are found as excesses ^{128}Xe$_n$, ^{129}Xe$_n$ and ^{131}Xe$_n$. A ^{129}I-^{129}Xe$_n$ chronometer appears to be especially suitable in Te-rich minerals since low-energy secondary neutrons are predominant and the chronometer may provide CRE ages in cases where production rates of commonly used nuclides are not known due to heavy shielding in large meteorites. Both reactions ^{128}Te(n, γ)^{129}Te, $\beta^- \rightarrow$^{129}I, and ^{130}Te(n, 2n) ^{129}Te, $\beta^- \rightarrow$^{129}I are reaction channels for the production of ^{129}I from Te nuclides. ^{129}Xe$_n$ is produced via decay of precursor ^{129}I; this presents the parent-daughter system that is used for the chronometry. GCR secondary neutron reactions on Te provide a system which is independent of shielding, as long as the exposure geometry remains constant.

Mathew and Marti (2008) improved the experimental techniques required for the Xe isotopic measurements in Te-rich troilite of iron meteorites. They showed that the neutron-produced excesses ^{129}Xe$_n$ and ^{131}Xe$_n$ show a linear correlation, and the slope identifies GCR epithermal neutrons as the prevalent source of particle reactions in Cape York troilite. Therefore the reaction excess ^{131}Xe$_n$ serves as a suitable monitor of GCR reactions and permits the calculation of the total excess ^{129}Xe$_n$.

4. Conclusions and Outlook

Although the GCR flux in the inner solar system is observed to be variable over a variety of time-scales because of solar modulation effects, longer time variations reflect changes in the local interstellar medium and in the sources of GCR. We discussed potentially useful nuclide pairs, which represent suitable GCR flux monitors for the time-scales of 1 Ma, 10 Ma and 100 Ma. Two of those methods were developed to the point that they can be used for flux calibrations. Other chronometers need to be further developed. For example, a very sensitive technique already exists for ^{53}Mn (3.7 Ma halflife) measurements by accelerator mass spectrometry (Korschinek *et al.*, 1987), while GCR-produced excesses on stable nuclide ^{53}Cr need to be assessed, but can be measured on multi-collector instruments with high precision. Calibrated average GCR fluxes over the one, ten and hundred million year time-scales are expected to provide the data required

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to assess the flux environment during recent crossings of star-forming and of inter-arm regions of the solar system. For average flux data for the entire circular motion in the galaxy an integration over longer time-scales is required. Therefore, it is desirable to improve isotopic abundance measurements of K in iron meteorites with documented one-stage exposure to GCR. This could provide average flux data over the time-scale of ^{40}K which corresponds to several revolutions of the solar system in the galaxy.

Among possible applications, the currently hypothetical connection between GCR flux variations and the terrestrial cloud cover is of interest. The implied temperature reductions and the appearance of ice ages need to be assessed (e.g. Calogovic *et al.*, this volume), once documentations of flux variations and of the time of crossing star-forming regions in the galaxy are known.

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Discussion

ANONYMOUS: When did the increase in cosmic ray flux by 38% occur?

MARTI: Less than 150 My ago, based on the 38% flux increase calibration.

ANONYMOUS: Is there any evidence on Earth of life extinctions through ozone loss, coincident with the penetration of GCR due to supernova explosions as might be expected when the solar system crosses a star forming region?

MARTI: The chronometers discussed in the talk aim at establishing the time of the last GCR-flux increase due to passage through a star-forming region. Results are not available at present. Ozone loss may be a possible result, but is not established.

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