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Assessment of ^{53}Mn deposition on Earth via accelerator mass spectrometry

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HIGHLIGHTS

- A novel approach to assess the ^{53}Mn deposition on Earth is proposed.
- 1400 l of snow from Antarctica were chemically processed to extract Mn and Be.
- ^{53}Mn/^{55}Mn and ^{10}Be/^{9}Be isotope ratios were measured by accelerator mass spectrometry.
- An upper limit for the ^{53}Mn global flux is established.

ABSTRACT

The ^{53}Mn flux onto Earth is a quantity relevant for different extraterrestrial and astrophysical questions. It is a proxy for related fluxes, such as supernova-produced material or interplanetary dust particles. In this work, we performed a first attempt to assess the ^{53}Mn flux by measuring the ^{53}Mn/^{10}Be isotopic ratio in a 1400 L sample of molten Antarctic snow by AMS (Accelerator Mass Spectrometry). Using the ^{10}Be production rate in the atmosphere, an upper limit of 5.5×10^{3} atoms cm^{-2} yr^{-1} was estimated for the deposition of extraterrestrial ^{53}Mn. This result is compatible with one of the two discrepant values existing in the literature.

1. Introduction

Earth continuously receives solid extraterrestrial material originating predominantly from asteroids, debris, and comets sublimation. These objects are usually classified by their size and most of them are in the form of interplanetary dust particles (IDPs) with radii between 5 and 250 μm (Cremonese et al., 2012). The radionuclides produced in these unshielded particles –through nuclear reactions induced by cosmic rays- are excellent tracers for the deposition of IDPs on Earth. In particular, ^{53}Mn is a long-lived radionuclide ($T_{1/2}$ = 3.7 Myr; Honda and Imamura, 1971) mainly produced through ^{nat}Fe(p, x) and ^{nat}Ni(p, x) reactions (Merchel et al., 2000). ^{53}Mn is poorly produced on Earth (see Section 4.2), and that is the reason why it is probably the most useful tracer to investigate several astrophysical issues. Two of them are the assessment of interstellar material flux produced by supernovae and the determination of the total IDPs flux entering into Earth.

The deposition of supernova-produced material has been studied with ^{60}Fe ($T_{1/2}$ = 2.6 Myr; Wallner et al., 2015) depth profiles in ocean ferromanganese crust by Knie et al., (1999, 2004). In these studies, the major uncertainty to estimate the flux of ^{60}Fe comes from the uptake of iron from the ocean water into the ferromanganese crust. The iron uptake factor can be calculated relative to the manganese uptake factor, which can be assessed by the ^{53}Mn flux (Knie et al., 2004; Fitoussi et al., 2008).

The ^{53}Mn flux is also useful for the assessment of IDPs influx, which can be estimated by means of the ratio between the ^{53}Mn global flux and its concentration in IDPs, providing a new and independent approach. The amount of accreted IDPs is today still poorly constrained,

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with an estimated range from 2 to 100 kt per year, obtained by different techniques (Plane, 2012 and references therein). IDPs fallen to Earth are accessible samples of extraterrestrial dust within the solar system. Moreover, the study of IDPs in geological environments may provide a retrospective insight into the solar system evolution (Genge et al., 2017 and references therein).

Decay counting techniques are unable to reach the necessary sensitivity to quantify the ^{53}Mn content. To overcome this difficulty, thermal neutron activation analysis has been used (Bibron et al., 1974; Imamura et al., 1979; Herpers, Sarafin, 1987). However, Accelerator Mass Spectrometry (AMS) –the most sensitive technique for the measurement of ^{53}Mn (Knie et al., 2004; Poutivtsev et al., 2010)– offers an alternative approach.

In this work, we propose to determine the ^{53}Mn global flux assuming that the ^{53}Mn/^{10}Be production ratio is roughly constant worldwide. The normalization with the ^{10}Be content circumvents uncertainties on atmospheric transport, deposition patterns, snow accumulation or erosion rates. As a proof of principle, we applied the proposed approach to 1400 L of molten snow collected at the Argentinian Carlini base in Antarctica. This location is close to the latitudinal range (50–60°S) where the flux of both ^{53}Mn and ^{10}Be is strongly enhanced (Dhomse et al., 2013).

2. Transport and deposition model

While entering the atmosphere, IDPs undergo a series of processes which include meteoric ablation and vaporization of the 90% on average of their mineral constituents (Taylor et al., 1998; Vondrak et al., 2008). The resulting metallic vapors form oxides or hydroxides and are polymerized to nanometer-sized particles known as meteoric smoke particles (MSPs).

From a general circulation model applied to the transport of MSPs to the lower stratosphere, Saunders et al. (2012) concluded that the MSPs are rapidly carried down to the stratosphere through the polar vortex, where they are assimilated by sulphate aerosols. Then, they are redistributed to middle-latitudes in the stratosphere. Finally, they enter the troposphere and are preferentially deposited on the Earth surface at latitudes between 50°S and 60°S preferentially. For a discussion of recent MSP transport see Dhomse et al. (2013).

In order to trace the atmospheric transport, deposition, snow accumulation and erosion processes, it is advantageous to use another cosmogenic long-lived radionuclide. ^{10}Be is mainly produced by spallation of N and O nuclei present in the atmosphere (stratosphere and troposphere) with a global production rate of 6.6×10^5 atoms cm^{-2} yr^{-1} (Masarik and Beer, 2009). ^{10}Be from extraterrestrial origin can be dismissed in comparison with the total ^{10}Be inventory (McHargue and Damon, 1991).

^{10}Be produced in the stratosphere has a residence time around 12–16 months in this atmospheric layer before entering troposphere, while ^{10}Be in the troposphere is only three weeks (McHargue and Damon, 1991) (Fig. 1).

The MSPs meridional mixing, the ^{10}Be attachment to ambient aerosols, and the long residence time of these aerosols, all processes taking place in the stratosphere, allow us to assume a uniform stratospheric ^{53}Mn/^{10}Be ratio worldwide. On the other hand, the residence time of ^{10}Be in the troposphere is too short to assume complete latitudinal mixing. So, when aerosols enter this atmospheric layer, the ^{53}Mn/^{10}Be ratio is altered and is no longer independent of the latitude.

The model proposed in this work assesses ^{53}Mn flux considering two different processes: a) the ^{53}Mn and ^{10}Be mixing in the stratosphere that allows to relate ^{53}Mn flux with the ^{10}Be global atmospheric production rate and then, b) the atmospheric transport and deposition that allows to relate the stratospheric ^{10}Be contribution with the local ^{10}Be deposition.

Following the arguments given above, we can assume that ^{53}Mn follows the same transport mechanisms as stratospheric ^{10}Be, therefore

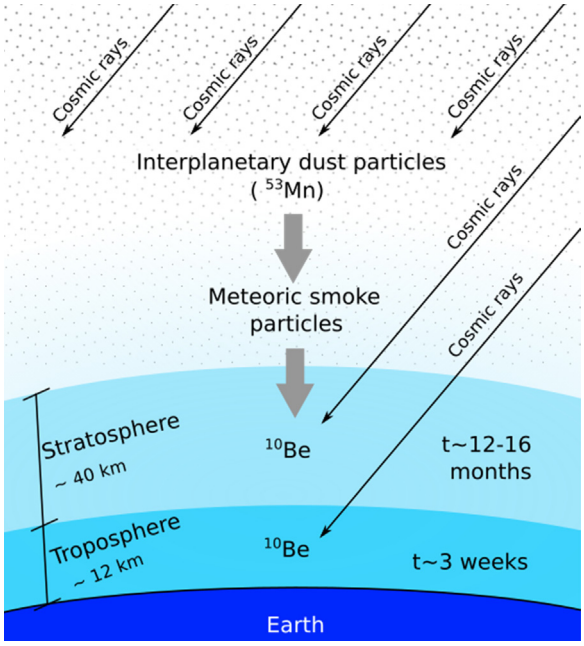

Fig. 1. Atmosphere layers' scheme where ^{10}Be is produced. The entry of extraterrestrial ^{53}Mn produced in IDPs is also represented.

the ^{10}Be tropospheric contribution must be subtracted from the global ^{10}Be production rate. Thus, considering that 65% of the ^{10}Be production takes place in the stratosphere, and the remaining 35% is produced in the troposphere (Heikkilä et al., 2009), the ^{10}Be stratospheric production rate $Pr_s(^{10}\mathrm{Be})$ yields 4.3×10^5 atoms cm^{-2} yr^{-1}.

On the other hand, to subtract the contribution of tropospheric ^{10}Be deposited at the sampling site, it has to be considered that according to Heikkilä et al. (2009) only 70% of the ^{10}Be deposited in that site comes from the stratosphere. Hence, the measured ^{10}Be concentration must be multiplied by a factor $f = 0.7$ to get rid of the ^{10}Be originating in the troposphere that was deposited at the sampling site. Then, the ^{53}Mn flux onto Earth can be determined as

$$\Phi(^{53}Mn) = [(^{53}\mathrm{Mn} \times Pr_s(^{10}\mathrm{Be})/(^{10}\mathrm{Be} \times f)]/A \quad (1)$$

where $A = 0.9$ represents the fraction of ablated and vaporized IDPs entering the atmosphere. Thus, the global ^{53}Mn deposition rate on Earth can be assessed from the ^{53}Mn/^{10}Be measured ratio in the snow sample.

3. Experimental procedure

3.1. Sampling

We studied a snow sample collected from Isla 25 de Mayo (King George Island) near the Antarctic Peninsula, in the ice field close to the Argentinian Carlini Base (62°14′18″S 58°40′00″W). This area presents a net average accumulation rate (water equivalent, w.e.) of 590 mm yr^{-1} (Rückamp et al., 2011). For the sampling year (2011), the weather station at the base has reported an annual precipitation rate of 330 mm w.e (SMN, 2016). The snow pit was about 1 m deep with a surface area of 4.5 m^2. The latitude of the sampling site (62° 14′ S) is close to the latitudinal range where the deposition of MSPs is most effective (50–60°S) (Dhomse et al., 2013).

The high precipitation rate at the sampling site in comparison to higher latitudes in Antarctica implies a dilution of the ^{53}Mn content. Thus, a large amount of snow (1400 L) was collected to achieve sufficient sensitivity for the detection of ^{53}Mn. The snow was gathered with a plastic shovel, transported to the base and stored in polyethylene bags. After melting the snow in plastic trays, it was stored in seven

Table 1
Mean average concentration values (given in ppb) for some stable isotopes present in the sample measured by ICP-MS.

Be	Mn	Fe	Ni
0.016(2)	3.24(2)	18.27(45)	0.080(4)

200 L polyethylene tanks.

3.2. Chemical processing

The 1400 L of molten snow were chemically processed at the TANDAR Laboratory in Buenos Aires. To allow the AMS measurement of the ^{10}Be and ^{53}Mn content in this sample, the chemical treatment had to extract beryllium and manganese from the sample. On the other hand, boron and chromium contained in the sample had to be suppressed, as ^{10}B and ^{53}Cr are, respectively, interfering stable isobars of ^{10}Be and ^{53}Mn. Be, Mn, Fe and Ni were measured by Inductively Coupled Plasma Mass Spectrometry (ICP-MS). These results are shown in Table 1.

Thus, the entire sample contained approximately 23 μg of beryllium and 4.5 mg of manganese. Manganese amount is close to the minimum necessary for a carrier-free chemical procedure and AMS measurement. A larger amount of stable manganese would imply a ^{53}Mn/^{55}Mn ratio below the current AMS detection limit (^{53}Mn/^{55}Mn > 10^{-14}; Poutivtsev et al., 2010).

For the ^{10}Be/^{9}Be AMS measurements an extra amount of 5.96(1) mg of beryllium was added to the entire sample. The isotopic ratio of the added Be material was ^{10}Be/^{9}Be = 9.16(76) × 10^{-15}, measured at VERA (Steier et al., 2004).

Since we are interested in the main source of ^{53}Mn –the ablated component of IDPs– the entire sample was passed through a 1 μm pore-size polypropylene filter to ensure that only this fraction of IDPs remained in the solution. The filtration excludes coarse particles such as the non-ablated IDPs fraction which represent a small contribution of 10% to the ^{53}Mn inventory and erosion debris of continental origin which contains ^{53}Mn-poor manganese. A contribution of the latter would have strongly decreased the sample ^{53}Mn/^{55}Mn ratio below the AMS detection limits. Thus, even if the measured ^{53}Mn/^{55}Mn ratio may not strictly reflects the actual ratio of the extraterrestrial material, the ^{53}Mn/^{10}Be ratio of the ablated material –from which the ^{53}Mn deposition is derived– should not be affected by the filtration procedure.

The sample volume was acidified adding seven liters of concentrated high-purity hydrochloric acid, reaching a concentration of 0.05 M HCl and it was then reduced using ten parallel ion exchange columns (5 cm in diameter), each of these containing 5 cm of Dowex 50WX8, 100–200 mesh cations resin. Mn, Be and the other cations were eluted with 4 L of 6 M HCl, with a recovery of ~ 80% (determined through the concentrations measured by ICP-MS before and after the elution). In this way, the cations present in the 1400 L sample were concentrated in a 4 L acidic solution. For a further extraction, the remaining sample was split by precipitation with NH_3 at pH~9 into two different fractions: a precipitate containing Be (and Al, Fe, etc.) and the aqueous fraction containing Mn (and Ca, Ni, etc.). The separation of Be and Mn from the other elements in each fraction was performed by ion exchange columns according to the procedure described by Merchel and Herpers (1999) adapted to the present sample size. Iron was extracted before the separation step using diisopropyl ether to prevent saturation of the ion exchange resins. Manganese was precipitated as $MnO(OH)_2$ from solution with $KClO_3$, washed three times with distilled water (18.2 MΩ cm), dried in an oven at 80 °C for 2 h, and then heated in a furnace at 500 °C for 2 h. The level of the interfering stable isobars of ^{10}Be and ^{53}Mn (^{10}B and ^{53}Cr) was reduced by means of this chemical procedure down to ppm levels. To assure thermal and electrical conductivity in the ion source, the sample material was mixed with Ag powder, in about 1:1 proportion by volume and pressed into two Ag sample holders.

3.3. Accelerator mass spectrometry measurements

The measurement of the ^{53}Mn/^{55}Mn ratio was performed using the Munich 14-MV tandem accelerator, which is able to provide the necessary energy for the suppression of the stable isobar ^{53}Cr by means of the gas-filled magnet GAMS (Knie et al., 1997). In this gas, Cr and Mn isobars have different mean charge states due to electron-exchange collisions and therefore follow different trajectories inside the magnet. In addition, an ionization chamber with segmented anode provides position-angle signal and discrimination in atomic number by the measurement of partial energy losses (Poutivtsev et al., 2010). For assessing the contribution of ^{53}Cr to the background a MnO_2 sample spiked with 1000 ppm of chromium was used, resulting in a suppression factor of 10^{-6}. The sample (divided in two holders) yielded mean $^{55}MnO^-$ currents of about 100 nA after the first mass selection, running for two hours until exhaustion. A terminal voltage of 12.3 MV was employed to accelerate $^{53}Mn^{11+}$ ions to an energy of 145 MeV. After applying all software gates, two events of ^{53}Mn could be identified. The ^{53}Mn concentration was finally determined relative to a standard sample (GRANT GLS), which has a ^{53}Mn/^{55}Mn ratio of 2.83(14) × 10^{-10}.

The ^{10}Be/^{9}Be ratio was measured at the Spanish Accelerator for Radionuclides Analysis (SARA), the 1 MV AMS facility at the Centro Nacional de Aceleradores in Seville, Spain (Ruiz-Gómez et al., 2010).

The ^{10}B isobaric interference was suppressed by a factor of ~10^5 by using a 100 nm thick silicon nitride passive absorber placed at the entrance of a 120° electrostatic analyzer. Background contribution from residual ^{10}B events was discriminated from ^{10}Be by means of a two-anode ionization chamber. It is worth to note that the isotopic ratio ^{10}Be/^{9}Be of the blank material used is far below the expected ratio in the sample (^{10}Be/^{9}Be ~ 10^{-9}), which is well above the AMS detection limit (^{10}Be/^{9}Be ~ 10^{-14}) at SARA.

4. Results

4.1. AMS results

Due to the low concentration of ^{53}Mn, and despite the large volume of the sample, only two counts compatible with this radionuclide were observed. Since the expected background contribution from ^{53}Cr was determined to be 1.35 events, an upper limit for the ^{53}Mn/^{55}Mn isotopic ratio was established at 7.6 × 10^{-13}. This value was calculated according to the Feldman, Cousins (1998) prescription. Considering the Mn concentration (Table 1), this result means that the ^{53}Mn concentration in the sample was less than 2.7 × 10^4 atoms per liter, with a 1-σ confidence interval. On the contrary, the ^{10}Be/^{9}Be ratio in the sample was well above the detection limit, and therefore an accurate value could be achieved. After carrier correction, the isotopic ratio was determined to be ^{10}Be/^{9}Be = 3.04(12) × 10^{-9}, which corresponds to 3.36(14) × 10^6 atoms per liter of sample. Then, the upper limit for the ratio of interest results to be ^{53}Mn/^{10}Be < 8 × 10^{-3}. It is worth to note that, since it is an upper limit, this value would not be incremented by a background correction.

4.2. ^{53}Mn global flux

Extraterrestrial ^{53}Mn is mainly produced by nuclear reactions of high-energy cosmic rays in IDPs, while terrestrial ^{53}Mn can be produced in iron-rich rocks. The latter could also contribute to ^{53}Mn content in the snow after erosion and transport processes. Schaefer et al. (2006) measured the terrestrial production rate as 103(11) atoms yr^{-1}(g Fe)$^{-1}$ and then Fujioka et al. (2010) fully validated this result. Thus, the iron content in our sample (about 28 mg according to Table 1) allow us to

estimate an upper limit to the amount of ^{53}Mn produced in an iron matrix, eroded by wind or rain and transported as dust into the snow sample. In the case the iron stems from rocks with very low erosion rates (< 10 cm/Myr), the rocks could have been exposed to cosmic rays for much longer periods than the ^{53}Mn lifetime. In that case, the iron present in the sample could have reached an equilibrium content of ^{53}Mn in the order of 10^7 atoms for our 1400 L sample, which would be comparable to the amount expected by IDP deposition. However, any erosion process with rates larger than 10 cm/Myr would make the contribution of the *in situ* production much lower than the extraterrestrial ^{53}Mn component.

Since each of the three parameters involved in Eq. (1) (A, *f*, and $Pr_s(^{10}Be)$) has a relative uncertainty of 15%, the uncertainty in the ^{53}Mn global flux is dominated by the upper limit obtained for the ^{53}Mn/^{10}Be ratio. Thus, the upper limit for the ^{53}Mn global flux is $\Phi(^{53}Mn) < 5.5 \times 10^3$ atoms cm^{-2} yr^{-1}. This result is compatible with the one reported by Imamura et al. (1979). In that work, the author studied deep-sea sediment cores using neutron activation technique with isotope enrichment and they published a ^{53}Mn global flux of 1.96(84) $\times 10^3$ atoms cm^{-2} yr^{-1}. On the other hand, the upper limit for the global flux obtained in our work is three standard deviations away from the value reported by Bibron et al. (1974), which is 18(4) $\times 10^3$ atoms cm^{-2} yr^{-1} (determined by neutron activation and X-ray spectrometry using snow samples from the Antarctic Plateau).

It has to be pointed out that the ^{53}Mn/^{10}Be ratio reported by Imamura et al. (1979), namely, 1.6(0.7) $\times 10^{-3}$, taken from a deep-sea sediment core at 10°57′S, 169°59′W, it agrees with our limit from Antarctica at 62°14′S, 58°40′W. This supports the hypothesis that the ^{53}Mn/^{10}Be ratio can be assumed to be roughly uniform worldwide.

4.3. Astrophysical implications

It was mentioned above (Section 1), that the total amount of IDPs accreted on Earth could also be deduced from the ^{53}Mn global flux as the ratio between this flux and the concentration of this radionuclide in IDPs. The latter value is very difficult to be assessed, as it depends on the trajectory of the IDPs in space, among other variables. An estimation of the ^{53}Mn content can be appraised considering that most of IDPs are originated in the Jupiter Family Comets orbiting between less than one and several astronomic units (AU) (Di Sisto et al., 2009; Nesvorný et al., 2010; Carrillo-Sánchez et al., 2016). Therefore, a reliable estimate of the ^{53}Mn content in IDPs requires the integration of solar and galactic cosmic ray contributions using the Jupiter Family Comets trajectories, which is far from the scope of this work.

Just as a rough estimation, we can consider that the IDPs origin is 3 AU away from Earth and that their trajectory is governed by the Poynting-Robertson effect (Kortenkamp and Dermott, 1998). Due to their dimensions, IDPs slowly spiral towards the Sun due to the Poynting-Robertson drag and the solar wind. Then, knowing the chemical composition of the IDPs, their exposure-time in space and the production-rate of a given radionuclide (^{53}Mn in this case) one can estimate the concentration of such radionuclide as done in Gómez-Guzmán et al. (2015). Each contribution (solar and galactic) to the production of ^{53}Mn in the IDPs can then be calculated using the specific production rate data and the elemental abundances in IDPs, assuming that IDPs have a similar composition to CI chondrite meteorites. Both galactic and solar productions rates are considered independent of the size of the IDPs in the calculations because homogeneous production within a given grain was assumed (Trappitsch and Leya, 2013).

The contribution from solar cosmic rays is obtained integrating the equation of motion over the spiral trajectory. According with the arguments given above, the solar production rate of ^{53}Mn at 1 AU corresponds to 963 dpm/kg. This value was obtained using the production rate on Fe (5.2×10^3 dpm/kg(Fe)) from Table 1 from Trappitsch and Leya (2013) and assuming the CI composition for IDPs. Considering that the flux of solar cosmic rays decreases with the square of the distance from the Sun, its contribution to the ^{53}Mn concentration was calculated to be about 49 dpm/kg for IDPs travelling during times around 1.5 Myr from 3 AU (the distance of the asteroid belt) to 1 AU.

The production rate of ^{53}Mn in IDPs due to galactic cosmic rays has been estimated to be around 558 dpm/kg(Fe) in secular equilibrium at 1 AU (Reedy, 1989). Considering again CI composition it results in 102.7 dpm/kg. From this value, the contribution from galactic cosmic rays for IDPs coming from 3 AU down to 1 AU was estimated to be about 19 dpm/kg. Therefore, the total effective concentration of ^{53}Mn in IDPs, integrating over the mass distribution extracted from Cremonese (2012), corresponds to a value of 68 dpm/kg (1.9×10^{14} ^{53}Mn at/kg). Using this value and the upper limit for ^{53}Mn global flux, it is possible to compute 150 kt/yr as an upper limit for the global flux of IDP onto Earth. This result is a factor 1.5 greater than the IPDs flux range upper limit reported in the literature (Plane, 2012).

Other potential application of the global ^{53}Mn deposition on Earth might be the determination of the interstellar material flux associated with supernovae. Knie et al., (1999, 2004) identified a peak in a ^{60}Fe depth profile in the ocean crusts in layers corresponding to an age of about 1.7–2.6 Myr. The 1-σ upper limit for the ^{53}Mn flux obtained in this work, allows us to calculate a lower limit for the Mn uptake factor (U_{Mn}). This factor can be calculated as the ratio between the ^{53}Mn flux incorporated into the crust, $\Phi_{crust,53Mn} = 1.7 \times 10^2$ atoms cm^{-2} yr^{-1} (measured by Knie et al., 2004) and the total flux constrained in our work, $\Phi_{tot} < 5.5 \times 10^3$ atom cm^{-2} yr^{-1}, yielding $U_{Mn} > 0.03$. With this constraint and using known concentration of elemental Fe and Mn in ocean water and in the crust, we calculated a lower limit for the iron uptake factor for that crust of $U_{Fe} > 0.005$. This agrees with the value reported by Knie et al. (2004), namely, $U_{Fe} \sim 0.006$. However, more recent works (Wallner et al., 2016; Breitschwerdt et al., 2016; Fry et al., 2016) estimate significantly higher values for the Fe uptake ($U_{Fe} \sim 0.1$) and consider an efficiency between 0.4% and 9% for ^{60}Fe atoms to get trapped in dust particles of the interstellar medium and to be able to enter the Solar System without being deflected by solar wind or interplanetary magnetic field.

5. Conclusions

This contribution presents a novel approach to assess the ^{53}Mn deposition on Earth. The two values found in the literature for the ^{53}Mn flux were both obtained by neutron activation and differ in one order of magnitude between each other. Our upper limit for the ^{53}Mn global flux, $\Phi(^{53}Mn) < 5.5 \times 10^3$ atoms cm^{-2} yr^{-1}, agrees with the result reported by Imamura et al. (1979) and is incompatible with the one given by Bibron et al. (1974). A lower limit for the iron uptake factor in marine crust and an upper limit for the flux of incoming IDPs were derived from the upper limit for the ^{53}Mn global flux.

The transport and deposition model proposed in this work depends on not well determined quantities, like the fraction of stratospheric produced ^{10}Be atoms from the total ^{10}Be deposited at the sampling site and the fraction of ablated and vaporized IDPs entering the atmosphere. Although these and other values are still not well known, the methodology presented is a promising approach for addressing extraterrestrial and astrophysical issues related to extraterrestrial ^{53}Mn deposition on Earth. In order to reduce the uncertainties, it would be desirable to study samples with a higher concentration of ^{53}Mn such as snow from Antarctic latitudes with lower precipitation rates.

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References

Bibron, R., Chesselet, R., Crozaz, G., Leger, G., Mennessier, J.P., Picciotto, E., 1974. Extra-terrestrial ^{53}Mn in Antarctic ice. Earth Planet. Sci. Lett. 21, 109–116.

Breitschwerdt, D., Feige, J., Schulreich, M.M., de Avillez, M.A., Dettbarn, C., Fuchs, B., 2016. The locations of recent supernovae near the Sun from modelling ^{60}Fe transport. Nature 532, 73.

Carrillo-Sánchez, J.D., Nesvorný, D., Pokorný, P., Janches, D., Plane, J.M.C., 2016. Sources of cosmic dust in the Earth's atmosphere. Geophys. Res. Lett. 43, 11979–11986.

Cremonese, G., Borin, P., Martellato, E., Marzari, F., Bruno, M., 2012. New calibration of the micrometeoroid flux on Earth. Astrophys. J. Lett. 749, L40.

Dhomse, S.S., Saunders, R.W., Tian, W., Chipperfield, M.P., Plane, J.M.C., 2013. Plutonium-238 observations as a test of modeled transport and surface deposition of meteoric smoke particles. Geophys. Res. Lett. 40–16, 4454–4458.

Di Sisto, R.P., Fernández, J.A., Brunini, A., 2009. On the population, physical decay and orbital distribution of Jupiter family comets: numerical simulations. Icarus 203, 140–154.

Feldman, G.J., Cousins, R.D., 1998. Unified approach to the classical statistical analysis of small signals. Phys. Rev. D. 57, 3873–3889.

Fitoussi, C., Raisbeck, G.M., Knie, K., Korschinek, G., Faestermann, T., Goriely, S., Lunney, D., Poutivtsev, M., Rugel, G., Waelbroeck, C., Wallner, A., 2008. Search for supernova-produced ^{60}Fe in a marine sediment. Phys. Rev. Lett. 101, 121101.

Fry, B.J., Fields, B.D., Ellis, J.R., 2016. Radioactive iron rain: transporting ^{60}Fe in supernova dust to the ocean floor. Astrophys. J. 827, 1.

Fujioka, T., Fifield, L., Stone, J., Vasconcelos, P.M., Tims, S.G., Champpell, J., 2010. In situ cosmogenic ^{53}Mn production rate from ancient low-denudation surface in tropic Brazil. Nucl. Instrum. Methods Phys. Res. B 268, 1209–1213.

Genge, M.J., Larsen, J., Van Ginneken, M., Suttle, M.D., 2017. An urban collection of modern-day large micrometeorites: evidence for variations in the extraterrestrial dust flux through the Quaternary. Geology 45 (2), 119–122.

Gómez-Guzmán, J.M., Bishop, S., Faestermann, T., Famulok, N., Fimiani, L., Hain, K., Jahn, S., Korschinek, G., Ludwig, P., Rodrigues, D., 2015. Accretion rate of extra-terrestrial ^{41}Ca in antarctic snow samples. Nucl. Instrum. Methods Phys. Res. B 361, 620–626.

Heikkilä, U., Beer, J., Feichter, L., 2009. Meridional transport and deposition of atmospheric ^{10}Be. Atmos. Chem. Phys. 9, 515–527.

Herpers, U., Sarafin, R., 1987. Determination of the spallogenic radionuclides ^{26}Al and ^{53}Mn in Antarctic meteorites with respect to cosmic ray exposure and terrestrial ages. J. Radioanal. Nucl. Chem. 11, 191–195.

Honda, M., Imamura, M., 1971. Half-life of ^{53}Mn. Phys. Rev. C 4, 1182–1188.

Imamura M., Inoue T., Nisiizumi K., Tanaka S., 1979. ^{53}Mn in Deep-sea sediments cores-an indicator of past solar activity. In: Proceedings of the 16th International Cosmic Ray Conference, 2.

Knie, K., Faestermann, T., Korschinek, G., 1997. AMS at the Munich gas-filled analyzing magnet system GAMS. Nucl. Instrum. Methods Phys. Res. B 123, 128–131.

Knie, K., Korschinek, G., Faestermann, T., Wallner, C., Scholten, J., Hillebrandt, W., 1999. Indication for supernova produced ^{60}Fe activity on earth. Phys. Rev. Lett. 83, 18–21.

Knie, K., Korschinek, G., Faestermann, T., Dorfi, E.A., Rugel, G., Wallner, A., 2004. ^{60}Fe anomaly in a deep-sea manganese crust and implications for a nearby supernova source. Phys. Rev. Lett. 93, 171103.

Kortenkamp, S.J., Dermott, S.F., 1998. Accretion of interplanetary dust particles by the Earth. Icarus 135, 469–495.

Masarik, J., Beer, J., 2009. An updated simulation of particle fluxes and cosmogenic nuclide production in the Earth's atmosphere. J. Geophys. Res. (Atmos.) 114, D11103.

McHargue, L.R., Damon, P.E., 1991. The global beryllium 10 cycle. Rev. Geophys. 29, 141–158.

Merchel, S., Herpers, U., 1999. An update on radiochemical separation techniques for the determination of long-lived radionuclides via accelerator mass spectrometry. Radiochim. Acta 84, 215–219.

Merchel, S., Faestermann, T., Herpers, U., Knie, K., Korschinek, G., Leya, I., Michel, R., Rugel, G., Wallner, C., 2000. Thin- and thick-target cross sections for the production of ^{53}Mn and ^{60}Fe. Nucl. Instrum. Methods Phys. Res. B 172, 806–811.

Nesvorný, D., Jenniskens, P., Levison, H.F., Bottke, W.F., Vokrouhlický, D., Gounelle, M., 2010. Cometary origin of the zodiacal cloud and carbonaceous micrometeorites: implications for hot debris disks. Astrophys. J. 713, 816.

Plane, J.M.C., 2012. Cosmic dust in the Earth's atmosphere. Chem. Soc. Rev. 41, 6507–6518.

Poutivtsev, M., Dillmann, I., Faestermann, T., Knie, K., Korschinek, G., Lachner, J., Meier, A., Rugel, G., Wallner, A., 2010. Highly sensitive AMS measurements of ^{53}Mn. Nucl. Instrum. Methods Phys. Res. B 268, 756–758.

Reedy, R.C., 1989. Cosmogenic-nuclide production rates in interstellar grains. in lunar and planetary science conference. Lunar Planet. Sci. Conf. 20, 888.

Ruiz-Gómez, A., Chamizo-Calvo, E., López-Gutierrez, J.M., García-León, M., Müller, A.M., Christl, M., 2010. On the measurement of ^{10}Be on the 1 MV compact AMS system at the Centro Nacional de Aceleradores (Spain). Nucl. Instrum. Methods Phys. Res. B 268, 733–735.

Rückamp, M., Braun, M., Suckro, S., Blindow, N., 2011. Observed glacial changes on the King George Island ice cap, Antarctica, in the last decade. Glob. Planet. Change 79, 99–109.

Saunders, R.W., Dhomse, S., Tian, W.S., Chipperfield, M.P., Plane, J.M.C., 2012. Interactions of meteoric smoke particles with sulphuric acid in the Earth's stratosphere. Atmos. Chem. Phys. 12, 4387–4398.

Schaefer, J.M., Faestermann, T., Herzog, G.F., Knie, K., Korschinek, G., Masarik, J., Meier, A., Poutivtsev, M., Rugel, G., Schlüchter, C., Serifiddin, F., Winckler, G., 2006. Terrestrial manganese-53: a new monitor of Earth surface processes. Earth Planet. Sci. Lett. 251, 334–345.

Steier, P., Golser, R., Kutschera, W., Priller, A., Vockenhuber, C., Winkler, S., 2004. VERA, an AMS facility for all isotopes. Nucl. Instrum. Methods Phys. Res. B 223, 67–71.

Taylor, S., Lever, J.H., Harvey, R.P., 1998. Accretion rate of cosmic spherules measured at the South Pole. Nature 392, 899.

Trappitsch, R., Leya, I., 2013. Cosmogenic production rates and recoil loss effects in micrometeorites and interplanetary dust particles. Meteorit. Planet. Sci. 48, 195–210.

Vondrak, T., Plane, J.M.C., Broadley, S., Janches, D., 2008. A chemical model of meteoric ablation. Atmos. Chem. Phys. 8, 7015–7031.

Wallner, A., Bichler, M., Buczak, K., Dressler, R., Fifield, L.K., Schumann, D., Sterba, J.H., Tims, S.G., Wallner, G., Kutschera, W., 2015. Settling the half-life of ^{60}Fe: fundamental for a versatile astrophysical chronometer. Phys. Rev. Lett. 114, 041101.

Wallner, A., Feige, J., Kinoshita, N., Paul, M., Fifield, L.K., Golser, R., Honda, M., Linnemann, U., Matsuzaki, H., Merchel, S., Rugel, G., Tims, S.G., Steier, P., Yamagata, T., S.R. Winkler, S.R., 2016. Recent near-Earth supernovae probed by global deposition of interstellar radioactive ^{60}Fe. Nature 532, 69–72.