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Calculation of ^{10}Be & ^{14}C Production Rates in the Solar Atmosphere: Implications for Solar Flare Spectral Index

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ABSTRACT

Production rates for the short-lived radionuclides ^{10}Be ($T_{1/2}$=1.36Myr) and ^{14}C ($T_{1/2}$=5730 yr) in the solar atmosphere were calculated. As both radionuclides are produced through spallation reaction of solar energetic particles (SEP) with oxygen as the primary target, the prevalence of each radionuclide is linked. For the calculations, we assumed power law distribution for SEP with spectral index, *r*, ranging from 2.5 to 4. We find the ^{10}Be and ^{14}C flux rate at the surface of the Sun to range from 0.007 $cm^{-2}\cdot s^{-1}$ to 2.55 $cm^{-2}\cdot s^{-1}$ for ^{10}Be, and from 0.13 $cm^{-2}\cdot s^{-1}$ to 24.13 $cm^{-2}\cdot s^{-1}$ for ^{14}C. These radio-nuclides are then entrained in the solar wind. From these flux rate calculations and comparison with experimentally measured flux rates, we find the most likely time averaged solar flare spectral index to be $r = \sim 3.3$.

Keywords: Solar Wind; Radio-Nuclide; ^{10}Be; ^{14}C; Solar Flare Parameter

1. Introduction

Particles that bombard the Earth's atmosphere originating from outside the Earth, broadly called here cosmic rays, come in three varieties: solar wind ions, SEP, and GCRs (galactic cosmic rays), differentiated primaries by their kinetic energies. Specific information about the cosmic ray type is given in **Table 1**.

Preliminary observations of solar wind ions began with the early space mission Lunik 2, Lunik 3, Venus probe, and Explorer 10; results from the Mariner 2 mission unequivocally demonstrated the existence of a continuous solar wind (e.g. [1]). Solar wind ions typically have energy of a few keV, so they typically do not participate in the production of cosmogenic nuclides. Solar wind ions can be implanted on the surface of extraterrestrial materials as they can penetrate to a depth of several hundred angstroms.

Direct evidence for the occurrence of solar wind implanted ions in extraterrestrial materials comes from lunar samples. Nishiizumi and Caffee [2] detected solar-wind-implanted ^{10}Be in Apollo 17 trench samples, and Jull *et al*. [3,4] measured solar-wind-implanted ^{14}C in Apollo 11, 16, and 17 soil samples. Lunar samples also contain surface implanted solar wind noble gases, including Ne and Ar [5].

Table 1. Cosmic Ray Parameters.

	Solar wind	SEP	GCR
Energy	0.3 - 3 keV	1 - 100 MeV	0.1 to > 10 GeV
Flux rate (nucl $cm^{-2}\cdot s^{-1}$)	3×10^8	200	2 - 4
Penetration depth	μm	cm	m

Lange and Forbush [6] were the first to detail solar flares after two exceptionally large flaring events in spring of 1942. Observations indicate that flaring can occur at any time, but flaring events are more likely and more energetic around solar maximums. Energy of the accelerated particles ranges from a few MeV/nucl up to several hundred MeV/nucl, with most of the particles having lower energy. The differential particle flux of energetic particles from the Sun behaves as a power law in kinetic energy *E*:

$$\frac{dF}{dE} \propto E^{-r}, \tag{1}$$

where dF/dE is the differential particle flux at Energy *E*, and *r* is the spectral index describing the flare; *r* typically ranges from 2.5 to 4.

Solar flares release large amounts of energy, and produce many energetic particles, including protons and various ions [7]. These SEP can interact with ambient gaseous target material in the solar atmosphere, producing daughter nuclei through nuclear reactions. Measurements of gamma-ray emission indicate nuclear interactions do occur at various depths in the solar atmosphere [8]. The radionuclides ^{10}Be and ^{14}C are examples of daughter nuclei which can be produced through spallation reactions with energetic particles originating in solar flares [9]. The main targets for ^{10}Be production are C and O, although O is the primary target, and the main target for ^{14}C production is also O. A portion of this spallogenic ^{10}Be and ^{14}C escapes the Sun and becomes entrained in the solar wind. Eventually some fraction of the solar wind radionuclides intersects the Moon, and becomes implanted on the lunar surface. As the solar wind ions typically have energies of about 1 keV/nucl, they are therefore implanted on the very surface, to a depth of up to ~30 nm [4]. Nishiizumi and Caffee [2] measured the surface correlated, *i.e.* solar wind ^{10}Be, in Apollo 17 lunar trench sample 78481, and find the ^{10}Be implantation rate to be ~2.5 × 10^{-6} cm^{-2}·s^{-1} at the surface of the Moon. This corresponds to an escape rate of ^{10}Be from the Sun of 0.1 cm^{-2}·s^{-1}. Jull *et al.* [3,4] measured the solar wind implanted ^{14}C in Apollo 11, 16, and 17 lunar soil samples, and from this data we find flux rate to be ~2 - 20 ^{14}C cm^{-2}·s^{-1} at the surface of the Sun. In this paper, we calculate the production rates for both ^{10}Be and ^{14}C in the solar atmosphere from SEP for a range of solar flare spectral indices. From these calculations, and comparison with experimentally determined solar-wind-implantation rates for each radionuclide at the lunar surface, we calculate the most likely time averaged solar flare spectral index.

2. Cosmogenic Nuclide Production

Nuclear spallation reactions occur when an incident energetic particle interacts with the nucleus of another atom, producing a cascade of secondary particles. For the reaction to occur, the incident particle must overcome the nuclear binding energy of the target atom. The lower energy secondary particles are free to induce lower energy spallation reactions of their own. Spallation reactions typically occur >10 MeV, but the threshold is dependent upon the type of incident particle and energy of the particle and the elemental composition of the target. Nuclear spallation reactions are typically of the type $a + X \to b + Y$, were a is the incident particle, X is the target, b is the secondary reaction product, and Y is the reaction product. Shorthand notation for this reaction is $X(a,b)Y$.

2.1. SEP Characteristics

We calculate the SLR production rates assuming the protons are characterized by a power law relationship:

$$\frac{\mathrm{d}F}{\mathrm{d}E} = kE^{-r}, \quad (2)$$

where r ranges from 2.5 to 4. From Reedy [10] we assume an integrated energetic proton flux of ~200 protons cm^{-2}·s^{-1} for E > 10 MeV at 1 AU. This corresponds to 9.3 × 10^{6} protons cm^{-2}·s^{-1} at the surface of the Sun.

2.2. Production Rate Calculation

The production rates for cosmogenic nuclides can be calculated via:

$$p = \sum_i N_i \int \sigma_{ij} \frac{\mathrm{d}F(E)}{\mathrm{d}E_j} \mathrm{d}E, \quad (3)$$

were i represents the target elements for the production of the considered nuclide, N_i is the abundance of the target element ($g \cdot g^{-1}$), j indicates the energetic particles that cause the reaction, $\sigma_{ij}(E)$ is the cross section for the production of the nuclide from the interaction of particle j with energy E from target i for the considered reaction (cm^2), and $\frac{\mathrm{d}F(E)}{\mathrm{d}E_j}$ is the differential energetic particle flux of particle j at energy E (cm^{-2}·s^{-1}) [7]. We assume gaseous targets of solar composition from Lodders [11], where the density of the photosphere is ~1 × 10^{-7} g·cm^{-3} [12].

2.3. Nuclear Cross-Sections

To calculate the production rate of ^{10}Be, we use the cross-sections from Gounelle *et al*. [13]. These are a combination of experimental data and model simulations from Sisterson *et al*. [14], Iljinov *et al*. [15], and Lange *et al*. [16]. For ^{14}C, we use the cross sections from Sisterson *et al*. [17], which are a compilation of experimental data.

We estimate the uncertainty associated with the cross sections to be roughly a factor of two. The reactions considered here are the main nuclear production pathways, taking into account both the abundance of the target material and the cross-section. Reactions not considered would most likely add little to the overall production rates.

3. Results

We use Equation (3) to calculate the production rates for both ^{10}Be and ^{14}C from SEP in the solar atmosphere. We use the integrated SEP flux of 9.3 × 10^{6} protons cm^{-2}·s^{-1} at the surface of the Sun for E > 10 MeV [10], and assume a power law distribution as in Equation (2), where r goes from 2.5 to 4. The cross-section functions and target are abundances are given in Sections 2.2 and 2.3, respectively. The results of production rate calculations from Equation (3) for a range of spectral indices for both ^{10}Be

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and ^{14}C are given in **Figure 1** below. **Table 2** also shows the results from Equation (3), and includes the predicted $^{14}C/^{10}Be$ production ratio.

The production flux rate for ^{10}Be ranges from 0.007 $cm^{-2}\cdot s^{-1}$ for r = 4 to 2.55 $cm^{-2}\cdot s^{-1}$ for r = 2.5. The production flux rate for ^{14}C ranges from about 0.13 $cm^{-2}\cdot s^{-1}$ for r = 4 to 24.13 $cm^{-2}\cdot s^{-1}$ for r = 2.5.

4. Discussion

Nishiizumi and Caffee [2] report the ^{10}Be flux rate at the surface of the Sun to be 0.13 ± 0.05 $cm^{-2}\cdot s^{-1}$. From the results presented in the previous section, and taking into account uncertainties in the cross-sections, we find that the time averaged spectral index must range from 3.1 to 3.4 in order to reproduce the measured ^{10}Be flux rate. The experimentally determined flux rate at the surface of the Sun for ^{14}C ranges from ~2 to 20 $cm^{-2}\cdot s^{-1}$ [3,4]. Taking into account uncertainties, calculations from the previous section indicate that the spectral index must range from 2.5 to 3.5 to reproduce the wide spread in ^{14}C measured flux rate.

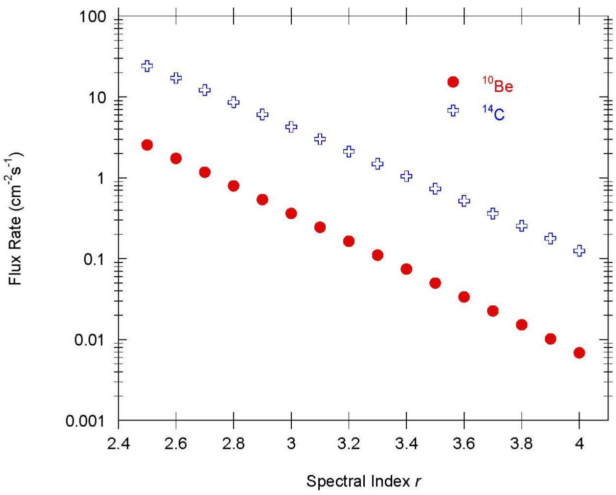

Figure 1. Production flux rate of ^{10}Be and ^{14}C from the spallation reaction on energetic protons on O target of solar abundance.

Table 2. ^{10}Be and ^{14}C flux rates, and $^{14}C/^{10}Be$ production ratios.

Spectral Index	^{14}C ($cm^{-2}\cdot s^{-1}$)	^{10}Be ($cm^{-2}\cdot s^{-1}$)	$^{10}Be/^{14}C$
2.5	24.13	2.55	9.46
2.6	17.13	1.73	9.88
2.7	12.13	1.18	10.32
2.8	8.57	0.80	10.78
2.9	6.05	0.54	11.27
3	4.27	0.36	11.78
3.1	3.01	0.24	12.31
3.2	2.12	0.16	12.87
3.3	1.49	0.11	13.45
3.4	1.05	0.07	14.06
3.5	0.73	0.05	14.69
3.6	0.52	0.03	15.35
3.7	0.36	0.02	16.04
3.8	0.25	0.02	16.76
3.9	0.18	0.01	17.50
4	0.13	0.007	18.28

The production of ^{10}Be and ^{14}C are connected in that the have oxygen as a common main target element. The production ratio of $^{14}C/^{10}Be$ is independent of the integrated particle flux as production rates scale linearly with incident particle flux rates. The $^{14}C/^{10}Be$ ratio is also independent of absolute elemental target abundances. The $^{14}C/^{10}Be$ ratio ranges from about 10 to 20, as depicted in **Table 2**. Using available ^{10}Be [2] and ^{14}C [3,4] data, the experimentally determined ratio for $^{14}C/^{10}Be$ at the surface of the Sun ranges from 20 to 200. It is feasible to simultaneously produce ^{10}Be at ~0.1 $cm^{-2}\cdot s^{-1}$ and ^{14}C at ~2 $cm^{-2}\cdot s^{-1}$, but it is not possible to simultaneously produce ^{10}Be at ~0.1 $cm^{-2}\cdot s^{-1}$, and ^{14}C at ~20 $cm^{-2}\cdot s^{-1}$.

Clearly, some other mechanism is needed to explain the higher ^{14}C ratio as calculations indicate simple solar wind implantation does not yield enough ^{14}C. One possible source is the spallation production from GCR at the lunar surface. Production of ^{10}Be from GCR is nearly negligible, but production of ^{14}C from GCR can occur in appreciable amounts [18]. It is possible that some of the “excess” ^{14}C can be attributed to GCR. Although beyond the scope of this paper, those calculations are needed to elucidate the ^{14}C contribution from sources other than the solar wind.

5. Conclusion

The production rates for both ^{10}Be and ^{14}C have been calculated in the solar atmosphere. The production rate we found for ^{10}Be was consistent with experimentally determined ^{10}Be rates with spectral index of 3.1 to 3.4. The ^{14}C production was also found to be consistent with experimentally determined ^{14}C rates with spectral index of 2.5 to 3.5. It is not possible to produce the measured $^{14}C/^{10}Be$ ratio with simple solar wind implantation for samples with a ^{14}C flux rate of ~20 $cm^{-2}\cdot s^{-1}$, indicating that a portion of the ^{14}C may be from GCRs. From the solar wind contribution of ^{10}Be and ^{14}C, we find the time averaged spectral index of the Sun to be ~3.3.

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