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Cosmogenic Evidences for Past SEP Events

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Terrestrial cosmogenic nuclides (such as ^{14}C, ^{10}Be, and ^{36}Cl) are mainly produced by galactic cosmic rays. In contrast, a certain amount of these nuclides is also produced by solar energetic particles (SEPs) derived from sporadic solar events such as solar flares and CMEs. Cosmic ray increase events in AD 774/775, AD 993/994 (or 992/993), and ~BC 660 have been discovered so far using ^{14}C data in tree rings (Miyake et al. 2012, 2013, Park et al. 2017). It is considered that the most plausible cause of these events is an extreme SEP event whose energy spectrum is very hard based on ^{14}C analyses of tree rings and ^{10}Be and ^{36}Cl analyses of ice cores (e.g. Mekhaldi et al. 2015, Miyake et al. 2015, 2019, Büntgen et al. 2018, O'Hare et al. 2019). These SEP events are estimated to be several dozen times larger than the largest events found in direct observation, which might have a serious impact on modern society. Therefore, it is important to investigate an occurrence rate of past extreme events. In recent years, surveys of past SEP events are actively conducted by cosmogenic nuclides measurements with high time resolution (~1-year resolution). Here, the detected past SEP candidates and a further survey of similar events are reviewed. This manuscript will be updated by 31 August.

cosmogenic nuclides
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1. Introduction

Solar Energetic Particles (SEPs) are caused by solar explosions such as solar flares and coronal mass ejections (CMEs), and SEPs are accelerated to high energy up to a few GeV. A phenomenon that the SEP flux increases largely at the earth is called a SEP event or a Solar Proton Event (SPE). Direct observations of SEP events have been made by satellites for the past ~50 years (e.g. GOES: Geostationary Operational Environmental Satellite). Add to the direct observations, ground detectors like neutron monitors have observed SEP events indirectly, i.e. SEP events with hard energy spectrum and/or large flux which can develop a cascade shower to the ground level (GLE), for a little bit longer period of the past ~70 years.

A large solar explosion does not necessarily cause an extreme SEP event, since it depends on the position of the solar surface where solar explosions occur, e.g. solar explosions occurred in the western side, especially around the western limb of the sun generate many SEPs arriving to the earth along the interplanetary magnetic field. Although a large solar explosion does not necessarily involve SEP events or geomagnetic storms which in particular have serious hazards on a modern society, extreme SEP events are often occurred by large solar explosions.

Although an understanding of extreme SEP events is very important issue for not only an elucidation of mechanism of particle accelerations but also the fields of space climate and solar physics, observational data for the past ~70 years alone do not provide information on longer-term behaviors of extreme SEP events, e.g. the frequency of extreme SEP events and the upper limit of size of events. A clue to these problems was shown by ^{14}C analyses of annual rings in 2012 (Miyake et al. 2012), i.e. it was shown that annual ^{14}C data can be used as a proxy data of past SEP events. Since then, annual ^{14}C data collection has been rapidly promoted. In this paper, it is introduced that how ^{14}C and other cosmogenic nuclides (^{10}Be and ^{36}Cl in ice cores) have been used in past SEP event studies, and the latest results of further SEP event searches in the past using cosmogenic data.

2. Proxy data of past extreme SEP events

2.1 Cosmogenic nuclides as proxy data of past SEP events

Cosmogenic nuclides such as ^{14}C, ^{10}Be and ^{36}Cl are produced by energetic particles, mainly galactic cosmic rays, in the atmosphere. Main channels of a production of ^{14}C is ^{14}N(n,p)^{14}C (neutron capture), and that for ^{10}Be and ^{36}Cl is spallation reaction such as ^{14}N(n,x)^{10}Be and ^{40}Ar(p,x)^{36}Cl (e.g. Beer et al., 2012). Since threshold energies of the production of these nuclides are above ~tens of MeV, high energy SEP particles can also produce enough amount of cosmogenic nuclides (e.g. Usoskin, 2017).

After the formation of cosmogenic nuclides in the atmosphere, ^{14}C is taken into tree rings as CO_2 after the global carbon cycle, on the other hand, ^{10}Be and ^{36}Cl are accumulated into ice sheets in the polar regions as a snowfall. Hence, the cosmogenic nuclide concentrations in archival samples such as tree rings and ice cores provide information of past cosmic ray intensities. Because SEP events occur in short time periods, as a typical time scale of hours to days, extreme SEP events should have been recorded as rapid spikes within 1-year in cosmogenic nuclides data.

2.2 Cosmic ray events shown in ^{14}C data

A tropospheric concentration of ^{14}C is observed as almost uniform on a global scale due to the global carbon cycle; hence, tree-ring ^{14}C data show similar values regardless of location. At the same time, tree-ring ^{14}C data reflect an attenuated and phase shifted variation of an original cosmic ray variation due to the carbon cycle. This is in contrast to ^{10}Be and ^{36}Cl, which can reflect more direct information of original cosmic ray variations than ^{14}C does, however, one needs to determine the cosmic ray variations from multiple ^{10}Be and ^{36}Cl measurements using different archive samples because they are easily affected by a deposition process (e.g. climate effect). If we can detect annual ^{14}C spike, even using only one archive sample, it may be possible to detect extreme SEP events.

From such a background, Miyake et al. (2012) conducted ^{14}C measurements using a Japanese cedar sample with annual resolution, and detected a sharp increase of ^{14}C concentration (~15‰) from AD 774 to 775. This increase is significantly larger than the normal ^{14}C annual variation found so far (~1‰ or less) and measurement accuracy of ^{14}C (2~3‰). This event has been then reproduced by ^{14}C analyses using tree samples from around the world (e.g. Büntgen et al. 2018). The ^{14}C increment of the 774/775 event has been estimated to be 2-3 times larger than the amount of ^{14}C atoms produced by ordinary galactic cosmic rays per 1-year (e.g. Büntgen et al. 2018), and several studies have shown that there was the short-term cosmic ray input in the spring-summer of AD 774 (e.g. Büntgen et al. 2018, Uusitalo et al. 2018). Subsequently, similar rapid ^{14}C increases were reported in AD 993/994 (Miyake et al. 2013), BC 3372/3371 (Wang et al. 2017), and ~BC 660 (Park et al. 2017).

2.3 Origin of cosmic ray events

Not only SEP events mentioned above, but also phenomena emitting gamma rays such as gamma ray bursts and supernovae, as well as comet impacts on the earth have been considered as causes for the rapid ^{14}C increases (e.g. Hambaryan and Neuhäuser 2013, Overholt and Melott 2013). In the case of the comet collision, diameter of a comet must be very large (~ 100 km) to cause the ^{14}C increases and such giant comet must leave a serios scar on the earth; however, there are not such craters corresponding to the cosmic ray events. Therefore, the comet hypothesis was denied (Usoskin and Kovaltsov 2015). Therefore, it is necessary to consider whether the gamma ray origin or the SEP (mainly proton) origin. Since it is difficult to pursue the problem using only a single ^{14}C data set to identify the cause, various verifications have been performed so far.

The first verification is to estimate the type and energy spectrum of the original particles by measuring concentrations of ^{10}Be and ^{36}Cl in ice cores and determining the production ratios between different nuclides. Measurements of ^{10}Be and ^{36}Cl concentrations in ice cores from Antarctica and Greenland have been conducted for the 775, 993/994, and BC660 events. In all of these events, rapid increases in nuclides concentrations have been detected in both hemispheres. Since it is estimated that gamma rays can produce insufficient number of ^{10}Be atoms to detect, because of its higher threshold energy of ^{10}Be production compared to protons, the existences of clear ^{10}Be peaks are grounds to deny the gamma ray origin (Pavlov et al. 2013). Also, the ^{36}Cl/^{10}Be ratio indicates that original particles are consistent with the SEPs whose energy spectrum is very hard (Mekhaldi et al. 2015, O'Hare et al. 2019).

The second verification is to investigate a north-south hemispheric symmetry and a latitude dependence appeared in ^{14}C and ^{10}Be data. In the case of the gamma ray origin, the hemispheric symmetry and the latitude dependence should not appear unless gamma rays entered under the limited condition, i.e. incident in equator vicinity, since gamma rays are not affected by geomagnetic field. Carbon-14 data using tree rings in worldwide locations and ^{10}Be data using ice cores from Greenland and Antarctica showed that a similar increment of nuclides concentrations in both hemispheres and a significant latitude dependence in ^{14}C data (Miyake et al. 2015, 2019, Mekhaldi et al. 2015, Büntgen et al. 2018, Uusitalo et al. 2018). These facts also support the SEP origin. For these reason, it is considered that the annual cosmic ray events detected in cosmogenic nuclides data reflect the SEP event.

3. Further search of past SEP events

4. Final remarks

In recent years, measurements of cosmogenic nuclides with high-time resolution (mainly ~1-year resolution) have been advanced rapidly for a past SPE exploration. For example, many researchers measured ^{14}C concentrations with 1-year resolution using different tree samples, and these data will be adopted in the next IntCal (^{14}C age calibration curve). Such collections of annual data continue, and hence it is expected that more long-term data will be obtained in the future. As past SEP event surveys require discussions using multiple archive samples and nuclides, it is important for researchers to collaborate and collect more data. Such data will provide more accurate information on the occurrence rate and the upper limit of SEP events.

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