Long-term solar/heliospheric variability: A highlight

Ilya Usoskin1)
Sodankylä Geophysical Observatory, University of Oulu, Finland

Abstract: Different heliospheric parameters are relatively well studied for the last decades of direct satellite and ground-based measurement. However, much less is known about their variability on longer time scales, where it needs to be studied using indirect methods. Here an overview of long-term reconstructions of solar/heliospheric variability on different time scales is presented. Reconstruction methods, including the method of cosmogenic isotopes $^{14}$C and $^{10}$Be recorded in natural archives, are described along with uncertainties and unresolved problems. Mechanisms of the cosmogenic isotope formation in the Earth’s atmosphere, their transport and deposition are discussed. The results of the reconstruction are presented for the long-term scale, from centennial to millennia that suggests a great range of solar/heliospheric variability spanning from very quiet Grand minima to extremely active Grand maxima.

Key words: Heliosphere, cosmic rays, long-term variability

1 Introduction

The very fact of the existence of the heliosphere was discovered relatively recently. As proposed by Parker [1], the permanently emitted solar wind should form a cavity in the interstellar space, controlled by the solar wind and the magnetic field, viz. by the solar magnetic activity. This cavity, of about 200 astronomical units across, is the heliosphere. Incoming cosmic rays of galactic origin experience modulation in the heliosphere, being scattered, convected, drifted and adiabatically cooled by the solar wind and the heliospheric magnetic field frozen into it.

The heliosphere and its parameters have been actively studied during the last decades, by using a number of dedicated space-borne missions, exploring both the inner part (inside the Earth orbit) and distant heliosphere. Much information has been gathered by ground-based instruments, including various types of cosmic rays detectors. However, all these measurements and observations cover a limited period of the last several decades. Active space-borne exploration started in the 1970s, while ground-based measurements extend for a few decades further back. This period corresponds to the very high level of solar activity, the modern grand solar maximum [2].

What can we learn about the past variability of solar/heliospheric parameters? Here indirect proxy may help, that keep information about solar variability on different time scales from centuries to millennia, as illustrated in Figure 1.

This review highlights recent achievements in the field of long-term reconstructions of solar variability, based on the method of cosmogenic radionuclides.

2 Method of cosmogenic radionuclides

When energetic cosmic rays imping on the Earth’s atmosphere, they collide with nuclei of atmospheric gases, most abundant being nitrogen, oxygen and argon. In such nuclear collisions, a wide variety of secondary particles can be produced, as illustrated in Figure 2. In particular, cosmogenic radionuclides can be produced. Most important for the long-term reconstruction of solar/heliospheric activity are two nuclides - radiocarbon $^{14}$C and $^{10}$Be. Details of their production, transport and archiving are given below.

1) E-mail: ilya.usoskin@oulu.fi

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Fig. 1. A scheme illustrating time spans covered by different data sets of solar/heliospheric variability. These include: direct spaceborne and ground-based measurements of heliospheric parameters and cosmic rays (upper line) since the 1950s; optical solar observation convertible into solar magnetic indices since the 1870s; geomagnetic indices since the mid-19th century; sunspot numbers since 1611; naked eye sunspot and aurora observations for the last millennium (however, they cannot yield a quantitative measure of solar activity); cosmogenic isotopes allowing presently for reconstructions over the Holocene (since ca. 9500 BC) but potentially expandable further back in time.

2.1 Cosmogenic Isotopes \(^{14}\text{C}\) aka Radiocarbon

Radiocarbon is formed when a thermal neutron, produced in the atmospheric cascade (see Figure 2), is captured by a \(^{14}\text{N}\) nuclei:

\[
^{14}\text{N} + n = ^{14}\text{C} + p. \tag{1}
\]

The maximum of production lies in the altitude range of upper troposphere – low stratosphere, where the flux of (super)thermal neutrons is maximum. Due to the additional shielding by the geomagnetic field, the isotope production is maximized in polar regions and is nearly half of that in the equatorial region [3]. Radiocarbon has half-life time of about 5730 years. In the atmosphere it gets oxidized to \(^{14}\text{CO}_2\) and, in the gaseous form, takes part in the global carbon cycle (see Figure 3). In the course of the carbon cycle, it gets completely (hemispherically) mixed in the atmosphere. A major part of the carbon cycle is related to the ocean with its huge carbon capacity and very slow response. Because of this, the production changes in the radiocarbon are greatly dumped in magnitude (e.g., the 11-year solar cycle is attenuated by a factor of 100) and also delayed [4]. Provided the ocean and atmospheric circulation cycle can be effectively reduced to a simple Fourier filter [5]. This assumption is well validated for the Holocene but cannot be extended further, to the ice age or the period of deglaciation. Unfortunately, it is very difficult to study details of the \(^{14}\text{C}\) production and cycle after the beginning of industrialization in the late 19-th century. The extensive burning of fossil fuel, which is highly inhomogeneous both spatially and temporally, produces the large amount of \(\text{CO}_2\), which is \(^{14}\text{C}\)-free, and dilutes the natural radiocarbon. Due to its global mixing and slow response, radiocarbon is almost insensitive to regional fast climate variability, but may be prone to slow trends in the ocean circulation/ventilation on millennial time scales. Radiocarbon is measured as \(\Delta^{14}\text{C}\), which is the normalized and corrected ratio of \(^{14}\text{C}\) to \(^{12}\text{C}\) [6]. Measurements are typically made for samples of tree-trunks, for which the annual tree rings allow absolute dating of the samples. Since radiocarbon is widely used in paleo-dating (e.g., of archeological artifacts), the calibration radiocarbon curve [7, 8] is well measured with decadal resolution for the last 25 millennia. This calibration curve presents the global \(^{14}\text{C}\) signal, as measured in tree samples from different

Fig. 2. A cartoon illustrating a cascade produced by cosmic rays in the atmosphere. Left-hand, central and right-hand branches indicate the soft, muon and hadronic components, respectively. Notations “N”, “p”, “n”, “μ”, “π”, “e±” and “γ” stay for nuclei, protons, neutrons, muons, pions, electrons and positrons, and photons, respectively. Stars denote nuclear collisions, circles - decay processes. (The cartoon does not represent all the details of the cascade.)
locations by a number of certified laboratories around the world. Thus, it presents a really global index which is almost free of any local or regional climate influence on the recorded signal.

2.2 Cosmogenic Isotope $^{10}\text{Be}$

Energetic cosmic rays and their secondaries can cause (Figure 2) nuclear spallation of atmospheric N, O and Ar, leading to production of trace amount of radioactive (half-life time about $1.4 \cdot 10^6$ years) isotope of $^{10}\text{Be}$. Beryllium-10 isotope is produced mainly in the lower stratosphere – upper troposphere [9]. After production, $^{10}\text{Be}$ gets attached to atmospheric aerosols. Because of their size and mass, these aerosols (and hence beryllium) can descend relatively quick. The residence time of Be in the stratosphere is about 1 year [10], thus it is not necessarily totally mixed. In the troposphere, its residence time is shorter – a few weeks. Thus, while the deposition of $^{10}\text{Be}$ is quite straightforward, it is highly dependent on the atmospheric circulation and precipitation pattern. $^{10}\text{Be}$ is usually measured in polar (Greenland or Antarctic) ice cores, which allow independent dating using glaciological methods. In contrast to the globally mixed radiocarbon, deposition of $^{10}\text{Be}$ has a pronounced geographical pattern, with the dominant precipitation at middle latitudes and relatively small deposition in polar regions [11, 12]. Because of this, concentration of $^{10}\text{Be}$ in ice core may be greatly affected by the local/regional climate/precipitation variability, particularly on the temporal scale shorter than 100 years.

In contrast to the global inter-laboratory $^{14}\text{C}$ calibration curve INTCAL [7, 8], presently there is no global $^{10}\text{Be}$ series combining all ice cores data. Accordingly, each series of $^{10}\text{Be}$ data from individual ice cores can be prone to local/regional climate variability, whose influence is difficult to estimate.

2.3 Comparison of the two isotopes

Both isotopes, $^{10}\text{Be}$ and $^{14}\text{C}$, are redistributed in the geosphere, but in quite different ways, as illustrated in Figure 3. While $^{10}\text{Be}$ is sensitive to changes in the large scale atmospheric dynamics and precipitation, which can be relatively fast (years–decades), radiocarbon is involved into the carbon cycle with very slow responding ocean circulation. Accordingly, any common signal in the two isotope records can be robustly ascribed to the production, viz. solar or geomagnetic, signal, since the terrestrial effects are clearly separated in the time domain.

A detailed comparisons between the two isotopes has been performed in different ways. First, Bard et al. [4] compared the South Pole $^{10}\text{Be}$ record and the $^{14}\text{C}$ data for the last millennium and found a good general agreement, when the effect of the carbon cycle is taken into account. Another approach has been applied recently [13], where the expected $^{10}\text{Be}$ signal was computed from the $^{14}\text{C}$ data and compared to several individual $^{10}\text{Be}$ series measured in different locations. A detailed analysis has shown that:
• $^{14}$C and $^{10}$Be data series agree with each other at time scales between 100 and 1000 year, implying the dominant solar signal.

• Agreement between $^{14}$C and any of the analyzed $^{10}$Be series appears better than the agreement between individual $^{10}$Be series. This implies that the local/regional climate plays an essential role in the short-term (inter-annual to decadal) time scale in the individual ice core $^{10}$Be records.

• There is a systematic discrepancy between the $^{14}$C and long-term Greenland (GISP and GRIP ice cores) $^{10}$Be records on the millennial scale in the early Holocene (cf. [14]). This discrepancy is probably related to the delayed effect of the last deglaciation via, e.g., the ocean circulation (affecting both $^{10}$Be and $^{14}$C) or precipitation pattern in the North Atlantic region (affecting mostly $^{10}$Be in Greenland). An additional independent proxy is required to resolve the discrepancy.

• The absence of agreement between the $^{10}$Be and $^{14}$C records on the short time scale (shorter than 100 years) is most likely related to the influence of the regional climate (depositional pattern) on $^{10}$Be content in ice cores, and, to lesser extent, to possible dating errors of the ice cores (may be up to a few decades).

Accordingly, the records of the two isotopes nearly perfectly agree on the centennial-millennial time scales, while multi-millennial scale can be affected by the global changes related to the deglaciation, and shorter (decadal) scale can be greatly distorted in $^{10}$Be records by the local/regional climate changes.

2.4 Summary of the method of cosmogenic isotopes

The main advantage of the method of cosmogenic isotopes is related to its OFF-LINE type. Primary archiving is done by the nature routinely in a similar manner throughout the ages (ice cores, sediments or tree trunks). Measurements are done nowadays in modern laboratories. If necessary, all measurements can be repeated and improved. Absolute independent dating of samples is possible: tree-rings provide absolute annual dating, while ice cores, marine sediments, etc., are usually dated with a reasonable accuracy of up to several decades in between volcanic tracers. As a result, a homogenous, of equal quality, data series can obtained for further analysis.

The main shortcoming of the method is related to the redistribution of the isotopes in the geosphere before the final archiving. This redistribution may distort the production (viz. solar activity) signal in the record and can be affected by local and global climate/circulation processes which are to a large extent unknown in the past. An assumption of the constancy of the transport/deposition processes can be more or less justified only for the Holocene (since ca. 9500 BC) but even during the Holocene some deviations from the perfect constant are possible. Records of $^{10}$Be in polar ice cores contain poorly known level of mixing in the atmosphere (thus preventing the absolute calibration to be done), and they are prone to short-term regional and long-term global transport variability. Radiocarbon $^{14}$C is globally mixed in the geosphere and thus is insensitive to short-term climate changes but it may be affected by changes in the large-scale ocean circulation (multi-millennial scales).

In order to resolve these uncertainties, a combined result from different proxy records is needed.

3 Solar/heliospheric variability on the long-term scale

A long-term reconstruction [2] of the solar activity quantified in the solar modulation potential $\phi$ [15] for the Holocene period (the last 11500 years), based on radiocarbon $^{14}$C record, is shown in Figure 4. Similar reconstructions can be obtained from $^{10}$Be records [14, 16], with a long-term discrepancy described above.

![Fig. 4. Long-term reconstruction of the solar modulation potential $\phi$ based on radiocarbon $^{14}$C data for the Holocene [2].](image)

Although uncertainties of the reconstruction can be essential [2, 14], with the largest uncertainty being related to the paleomagnetic reconstructions [17, 18], one can see several general features in the reconstruction.

• There is a slow trend in the solar activity variation with the reduced overall level ca. 1500 AD
There are clear periods of Grand minima of activity, visible as sharp dips of about 100 years duration. Identification of the Grand minima is quite robust and independent on the paleomagnetic uncertainties. In particular, all the Grand minima correspond to roughly the same level of activity, within the error bars. The Grand minima tend to cluster with a roughly 2400 year recurrence, with a clear $\approx 210$-year quasi-periodicity (Suess or de Vries period, see [20]) inside the clusters [21].

- Duration of the Grand minima [2, 22] tends to have a bi-modal distribution: shorter Maunder-like minima of 40–80-year duration and longer (100–140 years) Spörer-like minima.

- Sometimes the activity is very high, as, e.g., in the second half of 20-th century, corresponding to a Grand maximum state. Such Grand maxima appear seldom and irregular. Their duration typically does not exceed 70–80 years [2, 22]. Their occurrence is consistent with a Poisson random process [21]. Since their definition is not very stable and depends on the paleomagnetic reconstructions [17], it is uneasy to provide a solid analysis of such episodes.

- Solar activity is driven by an essential chaotic-stochastic component, leading to irregular variations and makes solar-activity predictions impossible for a scale exceeding that of the solar cycle [23].

- The Sun on average spends about 70% of time at the moderate magnetic activity level, about 15–20% of its time in Grand minima and about 10–15% in Grand maxima.

Considering the general features of solar activity over millennia, one can conclude that the last 400 years covered by the sunspot number series represent well the typical behavior of solar/heliospheric activity: both a Grand minimum (Maunder minimum) and a Grant maximum (the modern maximum) are present, covering the full range of the variability.

Since the solar radiative forcing drives the Earth’s climate, there have been numerical attempts to convert the reconstructed solar activity into the variable total solar irradiance (TSI) which is the main input for climate models. Many earlier TSI reconstructions were based on simple regression between solar activity and TSI during the last few decades (e.g., [24, 25]), and thus do not allow to evaluate possible errors. Recently, reconstructions based on physical models of the TSI formation appear [26, 27] but they still leave a room for large uncertainties. Therefore, the present level of knowledge makes a more or less robust reconstruction of solar variability possible for the last several millennia (the Holocene), but its application to paleoclimate models is still quite uncertain.

4 Summary

Cosmic rays in the heliosphere depict a great deal of variability. The main source of the cosmic ray variability on time scales from days to millennia is the solar magnetic activity with a slow addition of the geomagnetic field changes. While the apparent dominant feature is the (inverted) 11-year solar cycle, there is an essential centennial-millennial variability, which can be studied by an indirect proxy method. It is important that cosmic ray variations, via the cosmogenic isotopes archived in the geosphere, form the only source of information on the solar/heliospheric activity in the past. Cosmic-ray/solar variability can be reliably reconstructed for the Holocene (last 11 millennia) from the cosmogenic isotope data, although some uncertainties may exist in the long-term (millennial) trend and short-term (decades) variations, the latter due to the effect of local/regional climate on $^{10}$Be.

The level of solar/heliospheric activity varies between Grand minima and Grand maxima. Grand minima are clearly identified, have typical duration of 40–90 years (Maunder-like minima) or 100–140 years (Spörer-type minima), clustered with about 2400 years recurrence with a significant $\approx 210$-year quasi-periodicity inside the clusters. Grand maxima are less clearly defined, do not depict any apparent regularity in their occurrence, and have a typical duration of 40–80 years.

The Sun spends in these extreme states (Grand minima or maxima) about 70% of its time during the present evolution state. The major fraction of time (about 70%) the sun spends at the moderate magnetic activity level, typical, for example for the 19-th century, and which is likely to be in the nearest future [2, 22, 28].

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References