IL NUOVO CIMENTO **42 C** (2019) 43
DOI 10.1393/ncc/i2019-19043-8

Colloquia: SoHe3 2018

Long-term heliomagnetic field variation based on cosmogenic ^{44}Ti in meteorites

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received 28 December 2018

Summary. — Reconstructions of the heliospheric magnetic field (HMF) in the past centuries are mainly based on the analysis of sunspot activity, geomagnetic data or on measurement of cosmogenic radioisotopes stored in terrestrial reservoirs (tree rings and ice cores). There are, however, significant discrepancies among the results obtained by various techniques using different proxies of solar magnetic activity. In this work, new results obtained from a unique approach based on the measurement of the cosmogenic ^{44}Ti activity detected in meteorites are presented and compared with the most recent reconstructions of the near-Earth HMF strength. The very low level of ^{44}Ti activity in several meteorites fallen in the last 250 years was determined by using gamma-ray spectrometers (HPGe+NaI) located in the underground laboratory of Monte dei Cappuccini (INAF-OATo) in Torino, Italy. This approach, specifically designed to overcome the main problems affecting other methods, yields a powerful independent tool to reconstruct the long-term evolution of the HMF through the last two and a half centuries.

1. – Introduction

Proxy data such as sunspots, geomagnetic indices and cosmogenic radioisotopes (^{10}Be and ^{14}C) stored in terrestrial reservoirs like tree rings and ice cores allow insight into the long-term variability of the heliospheric magnetic field (HMF). Historical reconstructions based on the above proxies, however, have large uncertainties and are often discordant. Cosmogenic radioisotopes in meteorites, produced when they are exposed to galactic cosmis rays (GCRs) in the heliospheric space, offer an alternative tool for the investigation of the HMF variations in the past. These radioisotopes, produced directly in the meteoroid body in space, do not suffer from the terrestrial influences affecting ^{10}Be and ^{14}C

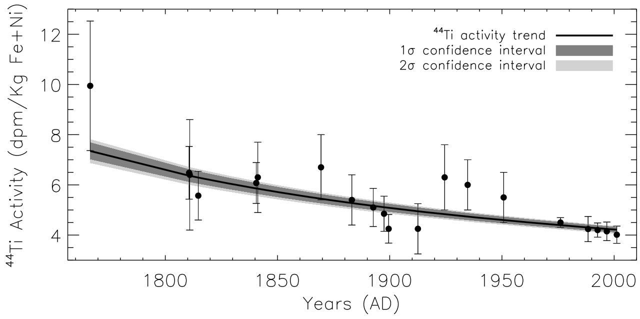

Fig. 1. – Time profile of measured ^{44}Ti activity (disintegrations per minute per kg of Fe + Ni) for meteorites fell between 1766 and 2001. Black dots depict measurements in meteorites. Error bars correspond to 1σ uncertainties. The black curve represents the trend of the ^{44}Ti activity. Dark- and light-gray shaded areas denote, respectively, 1σ and 2σ confidence bands.

like geomagnetic field, climatic changes, deposition rate variations, burning of fossil fuel and even nuclear bomb tests that tend to mask the modulation due to solar activity. By measuring the abundance of relatively short-lived cosmogenic radioisotopes in meteorites which fell in the past, it is possible to infer the variability of the GCR flux, since their production ends after the fall of the meteorite on Earth. ^{44}Ti is a radioisotope mainly produced by spallation reactions between GCR protons (> 70 MeV) with nuclei of Fe and Ni in meteoroid bodies. Because of its half-life of 59.2 ± 0.6 yr, ^{44}Ti represents an ideal index in meteorites for monitoring solar activity over the last two-three centuries. Here we show that measurements of ^{44}Ti activity in meteorites can be used for reconstructing the long-term evolution of the HMF over the last two and a half centuries.

2. – Analysis and results

The propagation of GCRs through the heliosphere is completely described by the transport equation derived by [1]. A simpler *force-field* approximation is often used in the literature, providing a useful parametrization of the modulation of the GCR flux. In this approximation, the transport equation is reduced to a simple convection-diffusion equation that depends on a modulation parameter $\phi = \phi(t, r)$, describing the modification of the local interstellar spectrum in the heliosphere as a function of time t and heliospheric distance r. Since the heliospheric modulation is ultimately defined by solar activity, the time-dependent parameter ϕ can be considered as a proxy of past solar global magnetic activity. The production rate of ^{44}Ti in meteorites depends on the GCR intensity in space. After the fall of the meteorites, this activity can be measured in laboratory since the radioactive decay chain $^{44}\mathrm{Ti} \rightarrow {}^{44}\mathrm{Sc} \rightarrow {}^{44}\mathrm{Ca}$ leads to the emission of γ-rays that are detectable with well designed γ-ray spectrometers. Figure 1 shows the ^{44}Ti activity measured in 20 stony meteorites which fell between 1766 and 2001 [2,3]. The measurements were performed at the Monte dei Cappuccini Laboratory (INAF–OATo) in Torino, Italy, by using selective and high-efficiency γ-ray spectrometers (HPGe+NaI). A detailed description of this system is given in [4,5,6,7]. The expected ^{44}Ti activity at a given time t is $A(t) = \frac{f}{\tau} \int_{-\infty}^{t} Q(t') e^{-(t-t')/\tau} dt'$, where $Q(t)$ is the ^{44}Ti production rate, $\tau = 85.4 \pm 0.9$ yr its mean life time and f is a scaling factor. Given the expected ^{44}Ti production rate Q in a stony meteorite as a function of ϕ [8], it is possible to solve

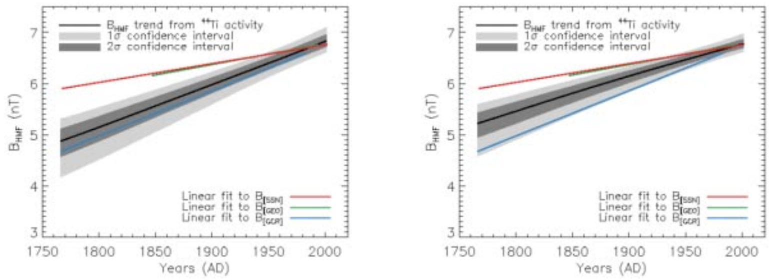

Fig. 2. – Trend of $B_{\rm HMF}$ between 1766 and 2001 (black line) obtained by using the $A(t)$ trend derived from measured ^{44}Ti data with 1σ and 2σ confidence bands. The plot in the left (right) panel was obtained by assuming constant (variable) solar wind speed (see text for details). Colored curves are linear fits to the sunspot-based, geomagnetic-based, and ^{10}Be-based composite reconstructions of the $B_{\rm HMF}$ given by [13,14].

the above equation as $Q(t) = \frac{\tau}{f}\left[\frac{dA(t)}{dt} + \frac{1}{\tau}A(t)\right]$ to infer the unknown $Q(t)$ dependence and thus recover the temporal evolution of ϕ, which will be directly related to the HMF strength.

A simple analytical function $A(t)$, representing the long-term evolution (or trend) of the observed activity, can be taken as the required input to solve the above problem. A common approach to the problem of trend extraction is given by fitting a low-order polynomial to the data or a simple analytical function of few parameters and adopting a comparison of the maximum likelihood of different analytic models. In deciding which specific model is the best, criteria are therefore needed allowing model comparisons to avoid both simplistic (underfitting) and overly complex (overfitting) models. Methods such as the Akaike and the Bayesian information criteria [9,10] provide relative ranks of competing non-nested models, also yielding a measure of confidence that each model is the most likely. According to the above criteria, a model represented by the analytical function $y(t) = t/(a+t)$ with best-fit parameter given by $a = -1526.2^{+10.7}_{-10.1}$ was proposed in [11] and selected as the best model for the trend of the ^{44}Ti activity for use in further analyses. Figure 1 shows the above trend, superimposed to the measured data, together with 1σ and 2σ confidence bands.

Given the functional form for $A(t)$, the time dependence of the production rate $Q(t)$, and consequently the temporal evolution of ϕ can be obtained. The time dependence of the HMF strength can be finally related to $\phi(t)$ according to $B_{\rm HMF}(t) = B_{\rm HMF,0}\left[\frac{\phi(t)v_{\rm sw,0}}{\phi_0 v_{\rm sw}(t)}\right]^{1/\alpha}$, where $v_{\rm sw}$ is the solar wind speed and the constants are normalization factors obtained by fitting data at Earth [12]. Here it is assumed that the exponent α has not changed in time due to its time invariant nature. By assuming constant solar wind speed, the trend is found to be linear and given by a $B_{\rm HMF}(t) = -9.879 + 0.00835t$ with t in years [11]. This relation implies that the HMF strength has varied from $4.87^{+0.24}_{-0.30}$ nT in 1766 to $6.83^{+0.13}_{-0.11}$ nT in 2001, with an overall average increment of $1.96^{+0.43}_{-0.35}$ nT over 235 years since 1766 (see left panel of Fig. 2). The colored curves in the same figure are linear fits to the sunspot-based, geomagnetic-based, and ^{10}Be-based composite reconstructions of the $B_{\rm HMF}$ as given by [13,14] and shown for comparison with our result. In addition to assuming constant solar wind speed, a possible linear relationship between $v_{\rm sw}(t)$ and $\phi(t)$ of the type $v_{\rm sw}(t) = m \cdot \phi(t) + q$, with $m = 0.23$ km s^{-1} MV^{-1}, and

$q = 303$ km s^{-1} was also proposed by [12]. We thus recalculated the long-term evolution of the HMF and found that, under this new assumption, the $B_{\rm HMF}(t)$ gradient would result less steep than in the constant speed case (see right panel of Fig. 2), implying a smaller average increment (by about 20%) over 235 years with respect to the one obtained by us in [11]. We remark, however, that this new result has to be taken with some caution: although the assumption of non-constant solar wind speed represents in principle an improvement with respect to the model worked out in [11], the hypothesis of linearity between $v_{\rm sw}(t)$ and $\phi(t)$ as proposed by [12] is actually debatable since this linearity is probably incorrect for a large fraction of the heliosphere, thus yielding even larger additional uncertainties in the derivation of $B_{\rm HMF}(t)$. A data-driven relation between $v_{\rm sw}(t)$ and $\phi(t)$ is thus desirable and will be investigated in a future work.

3. – Conclusions and future perspective

Several attempts have been made to reconstruct the long-term heliomagnetic field variation in the past [12,13,14,15]. The unique approach proposed in [11] and in this work for the reconstruction of the HMF strength, based on the measurement of the cosmogenic ^{44}Ti activity in meteorites, is designed to overcome most of the problematics that affected the previous efforts, thus yielding a powerful independent tool to reconstruct the long-term evolution of the HMF through the past few centuries. As such, the outcome of this work can be used as an independent check for future reconstructions. When compared with the linear fits to the sunspot-based, geomagnetic-based, and ^{10}Be-based composite reconstructions of $B_{\rm HMF}$ given by [13,14], the independent long-term variation obtained in this work is in agreement with the ^{10}Be-based reconstruction within a 1σ (2σ) confidence interval in the constant (variable) solar wind speed case. In both cases, the sunspot-based and geomagnetic-based reconstructions appear however to underestimate the slope of the overall trend when compared with the result obtained in this work, resulting in a flatter trend than evinced from our data. New measurements of the ^{44}Ti activity in meteorites that have been recently acquired by our group are ongoing through a much improved γ-ray spectrometer. These data will extend the investigated period by more than one decade, while possibly reducing the uncertainties in the HMF reconstruction.

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