

LETTER TO THE EDITOR

## Long-term solar activity reconstructions: direct test by cosmogenic $^{44}\text{Ti}$ in meteorites

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### ABSTRACT

**Aims.** Long-term solar activity in the past is usually estimated from cosmogenic isotopes,  $^{10}\text{Be}$  or  $^{14}\text{C}$ , deposited in terrestrial archives such as ice cores and tree rings. A number of such reconstruction models have been proposed which differ from each other significantly. This approach suffers, however, from uncertainties due to the sensitivity of the data to several terrestrial processes. Here we propose a method to constrain these solar activity reconstructions using cosmogenic  $^{44}\text{Ti}$  activity in meteorites which is not affected by terrestrial processes.

**Methods.** We test the veracity of recent solar activity reconstructions using the data on the activity of cosmogenic isotope  $^{44}\text{Ti}$  in meteorites which fell during the past 235 years, and provide an independent and direct measure of the cosmic ray flux near the Earth and allow decoupling of solar activity variations from terrestrial influences.

**Results.** We demonstrate that the  $^{44}\text{Ti}$  data can distinguish between various reconstructions of past solar activity based on cosmogenic isotope data in terrestrial archives, allowing unrealistic models to be ruled out. We also show that a model based on the sunspot number record is consistent with the data on  $^{44}\text{Ti}$  activity in meteorites, thus confirming the validity of the method. In particular the  $^{44}\text{Ti}$  data confirm significant secular variations of the solar magnetic flux during the last century.

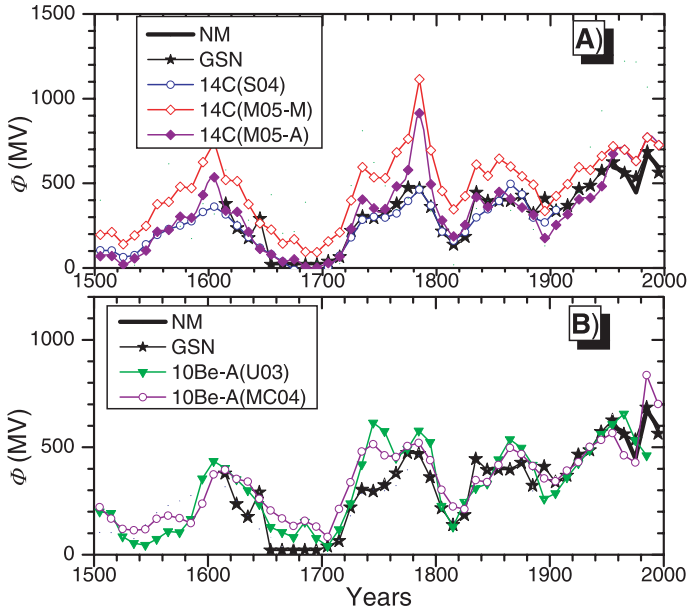
**Key words.** Sun: activity – Sun: sunspots – Sun: solar-terrestrial relations – Sun: magnetic fields

### 1. Introduction

Whereas the 11-year solar cycle is well documented, the long-term secular (centennial and millennial) variations of solar magnetic activity are still not well understood. Past solar activity levels are of considerable interest for the understanding of solar/stellar dynamos, as well as for solar-terrestrial relations and climate studies (e.g., Soon & Yaskell 2003). The longest direct index of solar magnetic activity, the sunspot number, only reaches back to 1610 AD. For longer periods, solar activity has been reconstructed from terrestrial records of  $^{14}\text{C}$  and  $^{10}\text{Be}$  produced in the Earth's atmosphere by cosmic rays (CR). The production rate of cosmogenic isotopes in the atmosphere is related to the CR flux impinging on Earth that is modulated by the heliospheric magnetic field and is thus a proxy of solar activity. However, the assumptions on which these reconstructions are based have been verified only for the last few decades when direct CR measurements became available, and their validity on longer time scales remains to be established. The measured concentration of  $^{14}\text{C}$  in terrestrial archives is related to its production rate, and thus to the CR flux, through a complicated carbon cycle, and has been strongly influenced by anthropogenic effects (fossil fuel burning and nuclear tests) during the last 100–150 years. This does not allow  $^{14}\text{C}$ -based reconstructions to be directly linked to the CR measurements during the last 50 years. Models based on  $^{10}\text{Be}$  data contain an unknown coefficient relating its measured value in ice cores to the atmospheric

production rate. The concentration of the cosmogenic isotopes in terrestrial archives is further affected by variable exchange rates within various terrestrial reservoirs, which need to be accurately taken into account. Another uncertainty is related to the geomagnetic field changes which also modulate the CR flux. All these variations are often not independently known. Several solar activity reconstructions, based on terrestrial cosmogenic isotope data, have been recently published by different groups on the millennium time scale (see Table 1), which differ from each other to a smaller or greater degree. Also, they may suffer from systematic effects. Therefore, there is a need for an independent method to verify/calibrate these results in order to provide a reliable quantitative estimate of the level of solar activity in the past, prior to the era of direct observations. Here we show that the  $^{44}\text{Ti}$  activity measured in meteorites serves as a unique and direct tool for selecting realistic models among different indirect reconstructions of solar activity.

Cosmogenic isotopes, produced in the meteoritic rocks during their exposure to CR in interplanetary space, provide a direct measure of the cosmic ray flux. The uncertainty due to imprecisely known terrestrial processes is naturally avoided in this case. Activity of a cosmogenic isotope in a meteorite represents an integral of the balance between the isotope's production and its decay, thus representing the time integrated CR flux over a period determined by the mean life of the radioisotope. By measuring abundance of cosmogenic isotopes in meteorites



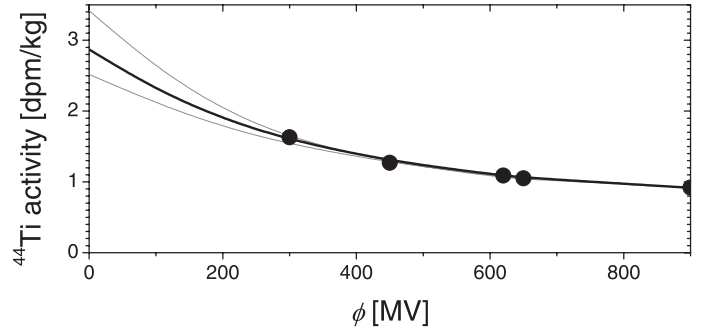
**Fig. 1.** Reconstructed decadal averages of the modulation parameter  $\phi$  for the last 500 years. Thick black curve (denoted NM in the legend) is based on direct cosmic ray measurements by neutron monitors since 1951 (Usoskin et al. 2005). Other notations correspond to Table 1.

which fell through the ages, one can evaluate the variability of the CR flux, since the production of cosmogenic isotopes ceases after the fall of the meteorite. A nearly ideal isotope for studying the centennial scale variability is  $^{44}\text{Ti}$  with the half-life time  $59.2 \pm 0.6$  yr (Ahmad et al. 1998), which is produced in nuclear interactions of energetic CR with Fe and Ni in the body of a meteorite (Bonino et al. 1995). Because of its mean life,  $^{44}\text{Ti}$  is relatively insensitive to variations of the cosmic ray flux on decadal (11-year Schwabe cycle) or shorter time scales, but is very sensitive to the level of the CR flux and its variations on a centennial scale.

In this Letter we compare predictions based on different long-term solar activity reconstruction models with the measurements of  $^{44}\text{Ti}$  in 19 stony meteorites (chondrites) which fell between 1766 and 2001, reported recently (Taricco et al. 2006), and show that measurements of  $^{44}\text{Ti}$  activity in meteorites can distinguish between different reconstruction models.

## 2. Test of solar activity reconstructions

The differential energy spectrum of galactic CR is often parameterized by the force-field modulation parameter  $\phi$ , which provides a quantitative measure of the cosmic ray modulation in the heliosphere (McCracken et al. 2004; Usoskin et al. 2005). Since the heliospheric modulation is ultimately defined by the Sun's magnetic activity, the parameter  $\phi$  is often considered as a proxy of past solar global magnetic activity. Recently  $\phi$  reconstructions spanning the last few centuries have been presented by different groups, that result from various models and are based on different data, i.e. group sunspot number (GSN),  $^{14}\text{C}$  in tree rings and  $^{10}\text{Be}$  in polar ice. However, the exact value of  $\phi$  depends on the assumed local interstellar spectrum (LIS) of CR which is not precisely known. The above mentioned groups used different assumptions regarding the LIS, and therefore we reduced all of them to the same basic modulation model of Castagnoli & Lal (1980), for compatibility. This is a straightforward conversion which takes into account slight differences in



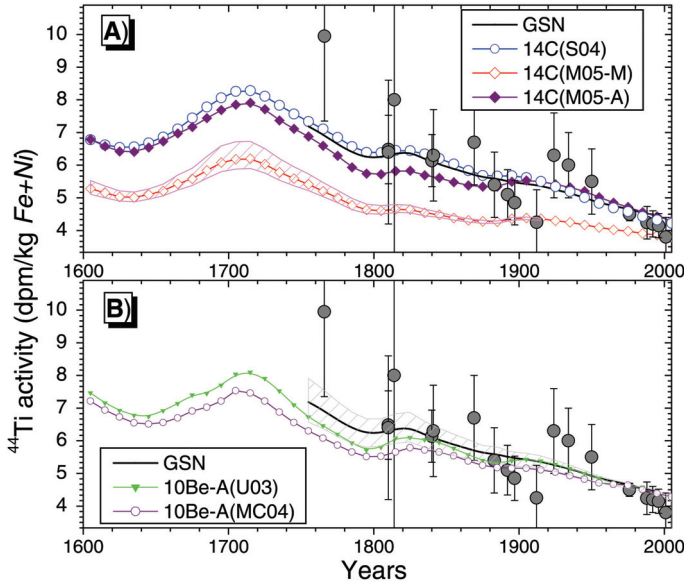
**Fig. 2.** Theoretical relation between the  $^{44}\text{Ti}$  production rate  $Q$  and the modulation parameter  $\phi$ . Dots depict the model computations (Michel & Neumann 1998), solid line – the best fit interpolation,  $Q = 0.8 + 2.07 \exp(-0.00319 \phi)$ . The shaded area covers the range of uncertainties of this relation, estimated by means of the bootstrap resampling method (Efron 1982).

the assumed LIS (see full details in Usoskin et al. 2005). Some of the reconstructions are plotted in Fig. 1, together with the values of  $\phi$  computed from CR fluxes measured by neutron monitors (NM) since 1951 (Usoskin et al. 2005). Here we compare various reconstructions with the actual  $^{44}\text{Ti}$  data in the following manner. From each  $\phi(t)$  curve we computed the expected  $^{44}\text{Ti}$  production rate in a stony meteorite,  $Q(t)$ , using the  $Q$ -vs- $\phi$  relation (Fig. 2) calculated by Michel & Neumann (1998). The uncertainties of this relation are small for high values of  $\phi$  but reach up to  $0.6$  [ $\text{dpm kg}^{-1}$ ] for  $\phi = 0$ . Then the expected  $^{44}\text{Ti}$  activity,  $A(t)$ , at a given time  $t$  can be computed as follows:

$$A(t) = \frac{1}{\tau} \int_{-\infty}^t f \cdot Q(t') \cdot \exp\left(-\frac{t'-t}{\tau}\right) dt', \quad (1)$$

where  $\tau = 85.4 \pm 0.9$  years is the mean life time of  $^{44}\text{Ti}$ , and  $f$  is a scaling factor, which corrects the calculated  $^{44}\text{Ti}$  activity for the actual concentration of target elements (Fe and Ni) and shielding depth in each meteorite (Bhandari et al. 1980; Michel & Neumann 1998; Neumann 1999; Cane 2003), thus making the measurements comparable with the theoretical calculations for a reference meteorite (Torino H6 chondrite, fall 1988). The value of  $f = 3.4$  corresponds to the chemical composition (Leya et al. 2000) and the pre-atmospheric size (about 20 cm at a shielding depth of 14 cm) of the reference Torino meteorite. Another minor correction is required because the meteorites usually originate from the asteroid belt with a typical aphelion around 2–3 AU (e.g., Gorin et al. 2004), where the CR modulation is slightly weaker than at 1 AU, for which  $\phi$  has been computed. A reduction in the values of  $\phi$  entering Fig. 2 by 1% accounts for the radial dependence of CR in the heliosphere (Caballero-Lopez & Moraal 2004). The  $^{44}\text{Ti}$  activity in a meteorite, thus corrected, is related to the average flux of CR integrated before the time of fall. Finally, we compare the  $^{44}\text{Ti}$  activity calculated above from different  $\phi$ -series with the actual measurements of  $^{44}\text{Ti}$ .

In Fig. 3 we compare the  $^{44}\text{Ti}$  measurements in the 19 meteorites with the calculated  $^{44}\text{Ti}$  activity,  $A(t)$ , resulting from models shown in Fig. 1. Data from all individual meteorites have been normalized, using shielding factors, to the reference Torino meteorite and recalculated to the immediate  $^{44}\text{Ti}$  activity,  $A$ , at the time of the meteorite's fall (see details in Taricco et al. 2006). An important result is that the GSN-based curve, which is a model computation (Solanki et al. 2002) rather than an indirect reconstruction, follows the data reasonably well. This confirms



**Fig. 3.** Immediate  $^{44}\text{Ti}$  activity in stony meteorites as a function of time of fall (Taricco et al. 2006). Large dots depict measurements in meteorites: Albareto (year of fall 1766), Charsonville (1810), Mooresfort (1810), Agen (1814), Cereseto (1840), Grüneberg (1841), Kernouvé (1869), Alfianello (1883), Bath (1892), Lancon (1897), Holbrook (1912), Olivenza (1924), Rio Negro (1934), Monze (1950), Dhajala (1976), Torino (1988), Mbale (1992), Fermo (1996) and Dergaon (2001). Error bars correspond to  $1\sigma$  uncertainties in the  $^{44}\text{Ti}$  activity. Curves correspond to the theoretically expected  $^{44}\text{Ti}$  activity based on the different  $\phi$  reconstructions shown in Fig. 1. Results based on original data are represented by symbols connected with a line, while the data extensions (see text) are indicated by symbols only. The hatched areas for the 14C(M05-M) curve in panel A and for the GSN curve in panel B reflect the uncertainties of the  $Q$ -vs.- $\phi$  relation (see Fig. 2).

the correctness of theoretical models relating GSN to the modulation potential  $\phi$  and the expected  $^{44}\text{Ti}$  activity, and provides a solid basis for quantitative tests of other indirect reconstructions. The other curves in Fig. 3 reproduce the data at different levels of accuracy, and we applied a  $\chi^2$  quantitative test to evaluate the agreement between the model curves and the data. In Table 1 we list the  $\chi^2$  values, the number of degrees of freedom (meteorites used) and confidence levels. The first set of columns is for the original data sets. All series are compatible with the measurements at the 87% level or better, except for 14C(M05-M) which should be rejected at a significance level of 99%.

While all the  $\phi$ -series start well before the fall of the earliest analyzed meteorite (1766), they stop at different times, leading to different numbers of meteorites used in this comparison (Table 1). We have therefore also created data sets of homogeneous length by combining the various reconstructed  $\phi$ -series in the following manner: the GSN series was not modified; the 14C(S04) series was extended after 1900 using the GSN-based series; all  $^{10}\text{Be}$ -based series were extended by the NM series (see Fig. 1) after 1980; 14C(M05-M) and 14C(M05-A) were extended after 1995 using the NM series based on (Masarik & Beer 1999). This extension allows four recent meteorites (1988–2001), which are the most precisely measured, to be included in the analysis. Note that this extension does not exceed the half-life period of  $^{44}\text{Ti}$  (except for the 14C(S04) series), so that the  $^{44}\text{Ti}$  activity computed for the 1990s is mostly defined by the original series, and the extended series plays only a minor role. The  $\chi^2$  statistics computed for these extended curves are given in the second set of columns of Table 1. Clearly, these

**Table 1.** Test of agreement between theoretically expected and measured  $^{44}\text{Ti}$  activity in meteorites. Different reconstructions of the modulation parameter  $\phi$  (Fig. 1) are denoted as follows: GSN – reconstruction (by Usoskin et al. 2002) based on group sunspot numbers; 14C(S04) – reconstruction (by Solanki et al. 2004) based on  $^{14}\text{C}$  in tree-rings; 14C(M05-M) and 14C(M05-A) are the main and alternative reconstructions, respectively, (by Muscheler et al. 2005) based on the same  $^{14}\text{C}$  data; 10Be-G(U03) and 10Be-G(MC04) represent reconstructions (by Usoskin et al. 2003, 2004b and by McCracken et al. 2004, respectively), based on  $^{10}\text{Be}$  in Greenland ice; 10Be-A(U03) and 10Be-A(MC04) are reconstructions (by Usoskin et al. 2003, 2004a and by McCracken et al. 2004, respectively), based on  $^{10}\text{Be}$  in Antarctic ice. Column 2 shows the time when the original analyzed series stops. The values of  $\chi^2$  statistics and the number of meteorites used (in parentheses) are listed in Cols. 3 and 5 for the original and extended data sets (see text), respectively. The confidence level,  $P_0$  in %, that the model is compatible with the measurements (Fig. 3), is given in Cols. 4 and 6.

$\phi$ -series	Period until	Original $\chi^2$ (d.o.f.)	$P_0$	Extended $\chi^2$ (19)	$P_0$
GSN	2002	10.9 (19)	93	10.9	93
14C(S04)	1900	3.7 (10)	96	10.1	95
14C(M05-M)	1996	35.3 (18)	1	35.4	1
14C(M05-A)	1996	11.2 (18)	88	12.1	88
10Be-G(U03)	1985	8.5 (15)	90	10.6	93
10Be-G(MC04)	1985	8.9 (15)	88	9.7	96
10Be-A(U03)	1985	8.4 (15)	90	9.8	96
10Be-A(MC04)	1985	9.1 (15)	87	10.6	94

extensions do not significantly change the results and conclusions. In general, the confidence level is increased, so that most of the reconstructions are now compatible with the measurements at a confidence level of 88% or better. The 14C(M05-M) curve still contradicts the measurements.

The extended  $^{44}\text{Ti}$  data set and the model computations also allow a verification of the model reconstruction of the solar open magnetic flux, which exhibits a significant secular variation, including nearly a doubling over the last century (Lockwood et al. 1999; Solanki et al. 2002). For example, if one assumes a constant open magnetic flux over the last 400 years (at a level equal to  $9.4 \times 10^{14}$  Wb, which corresponds to the average during the last 50 years), the corresponding value of  $\chi^2(19) = 36$ , which implies that this hypothesis should be rejected with a probability of 99%. On the other hand, the GSN model (which is consistent with the model by Solanki et al. 2002) discussed here is in good agreement with the  $^{44}\text{Ti}$  data.

### 3. Conclusions

We have shown that the  $^{44}\text{Ti}$  record in meteorites offers an excellent test of the solar activity reconstructions in the past as it is free of not precisely known terrestrial effects. By comparing recent long-term reconstructions of solar activity (in the form of the modulation potential  $\phi$  or the Sun's open magnetic flux) with the actual  $^{44}\text{Ti}$  measurements in meteorites, we have verified the reliability of different reconstructions and are able to distinguish between them. In particular, we conclude that the model based on group sunspot numbers via the open magnetic flux (Solanki et al. 2002; Usoskin et al. 2002) is in a good agreement with the  $^{44}\text{Ti}$  record, thus confirming the validity of the method. We have thus shown that most recent reconstructions of solar activity, in particular those based on  $^{10}\text{Be}$  data in polar ice (Usoskin et al. 2003, 2004b; McCracken et al. 2004) and on  $^{14}\text{C}$  in tree rings (Solanki et al. 2004), are consistent with the  $^{44}\text{Ti}$  data. On the other hand, the  $^{14}\text{C}$ -based model by

Muscheler et al. (2005) predicts too low cosmic ray flux (too high solar activity) during the last four centuries and is inconsistent with the  $^{44}\text{Ti}$  data. The Muscheler et al. model 14C(M05-M) can thus be ruled out. Better precision of the  $^{44}\text{Ti}$  activity measurements should enable us to provide further constraints on various reconstructions based on terrestrial archives.

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