Solar Physics (2004) 224: 387–392

SOLAR ACTIVITY RECORD FROM ARCHEOMAGNETIC DATA

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(Received 1 September 2004; accepted 18 October 2004)

Abstract. Each of the available solar activity (SA) proxy data (historical notes, radio nuclides ^{14}C and ^{10}Be production) are contaminated by their specific noise factors. So, any additional proxy with its independent noise factors will essentially increase the accuracy of composite SA restorations. It is proposed here that archaeomagnetic measurements 95% confidence interval (α_{95}) may serve as new proxy for the SA estimation in the past. This proxy is compared with other available proxies during the years 1500–2000.

1. Introduction

Regular solar activity observations cover the period of the last three centuries and indirect (proxy) data need to be used to effect longer time scale solar activity (SA) estimation (see, e.g., Ogurtsov *et al.*, 2002). Each of the proxies is contaminated by additional factors and has dating and (or) amplitude uncertainty increasing from present time to the past. Proxies derived from historical notes of both direct observations of the Sun (Wittmann and Xu, 1987) and Aurora Borealis observations (Schove, 1955; Silverman, 1998) are dependent on the political and social situations of the corresponding historical epoch. SA estimation from global ^{14}C concentration (Stuiver, Reimer, and Braziunas, 1998) needs an adequate carbon reservoir model and independent accurate measurements of the geomagnetic moment. Local ^{10}Be data (Beer *et al.*, 1990; Bard *et al.*, 2000; Usoskin *et al.*, 2004) indicate geomagnetic field secular variations and a number of geochemical processes besides SA. In this situation, only several independent proxy records should be used for the most precise SA restoration and any new independent record may essentially improve our knowledge about SA in the past.

2. Data

We have used data stored in the IAGA archeomagnetic directional database (Tarling and Dobson, 1995). These measurements to effect historical geomagnetic field secular variations are based on the methods of Thellier and Shaw or their modifications (see, e.g., Valet, 2003). It is supposed that the sample under investigation, e.g. brick or lava, was heated above the Curie temperature. During the transition through the Curie point the sample loses its natural magnetic moment and the magnetic orientation of the sample's magnetic domains become chaotic. When the sample is cooled, it "remembers" the geomagnetic field, which exists around it during the cooling process. The age of the sample is determined from archaeological sources or from the radiocarbon dating procedure (Lanos, Kovacheva, and Chauvin, 1999).

In our investigation we use only confidence interval α_{95} (directional cone radius, measured in degrees) as the informative parameter. This parameter is determined by means of statistical data analysis for a series of samples (as a rule 7–11 samples), which are taken from the same place.

3. Methods and Results

We had to remove data with age uncertainty (DE) greater than 30 years so that well-known SA global extrema (Gleissberg cycle) could appear in the resulting curve. Data with no a α_{95} estimation were also removed. We calculated average confidence interval ($\langle\alpha_{95}\rangle_{30}$) for the remaining measurements (77 for the period 1700–2000 A.D.) on a 30-year-long (DE) sliding window to reduce the dispersion of data. The dispersion of initial α_{95} data is large enough due to SA day-to-day variability (the rate demagnetization–magnetization process of archaeomagnetic samples rarely exceeded several days). The inverse value

$$M\alpha_{95} = f/\langle\alpha_{95}\rangle_{30} \tag{1}$$

was calculated to follow the physics of the phenomenon (see Sections 4 and 5). Scaling factor $f = 180$ is chosen as a radius of the full open directional cone. Outsiders (spikes) of the time series Mα_{95}(t) appearing due to inhomogeneous data coverage within DE sliding window were removed by a standard smoothing spline procedure.

In Figure 1 averaged within DE window points of Mα_{95}(t) are shown with DE/2 sampling rate. Other proxy records are also averaged in the same manner. The correlation coefficient between smoothed sunspot numbers Wnr (Zurich series) and Mα_{95} during 1700–1960 year is $r = 0.84$. It is of the same order ($r = 0.82$) for the Group Sunspot Numbers GSN (Hoyt and Schatten, 1997) and Mα_{95} during 1630–1960. Joint analysis of the multiple proxy records leads us to some simple conclusions, which can be seen directly from Figure 1:

- Radionuclide production (Rp) compiled by Bard *et al.* (2000) is widely known as one of the basic series for the total solar irradiance reconstructions. We can see in Figure 1, that Rp shows the later Dalton minimum (beginning of 19th century) than it is shown by GSN, Wnr and Mα_{95}.
- Extended sunspot numbers (Wnr) by Nagovitsyn (1997), GSN and Mα_{95} show that the fall to the Maunder minimum (middle of 16th century) was somewhat quicker than is shown by Rp.

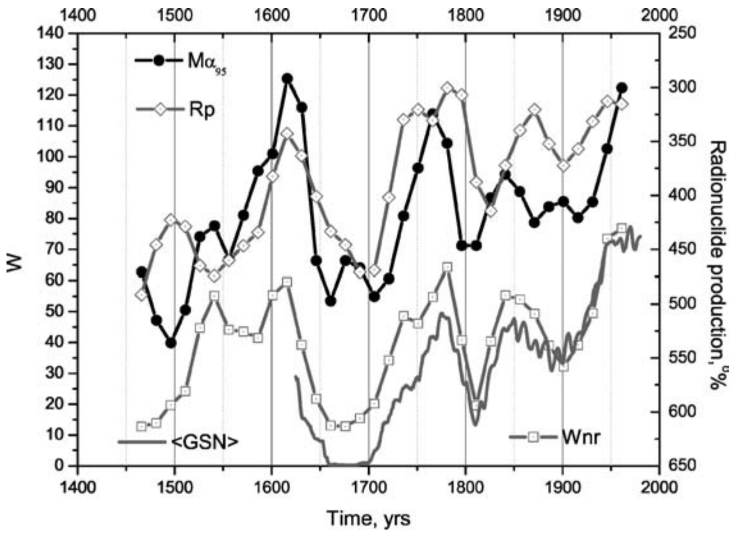

Figure 1. Comparison of the new $M\alpha_{95}$ proxy with other solar activity proxies. Wnr – extended sunspot numbers, Zurich series, by Nagovitsyn (1997). GSN – group sunspot numbers by Hoyt and Schatten (1998). Rp – radionuclide production by Bard *et al.* (2000). All presented data are averaged by a 30-year-long sliding window. Indirect proxies $M\alpha_{95}$, Wnr, and Rp have 15-year sampling rate, GSN have a 1-year sampling rate.

– It is more likely that the small maximum after the Spoerer minimum was centered at 1540 year as it is shown by both Wnr and $M\alpha_{95}$, i.e., about 40 years later than is shown by Rp. It is more likely that this maximum had relatively small amplitude as is shown by both Rp and $M\alpha_{95}$ (not shown by Wnr).
– Compared with other SA proxy records $M\alpha_{95}$ precisely indicates the positions of SA global maximums but it may have some relatively small spikes during the minima. These spikes can be seen (Figure 1) in the center of the Maunder minimum and the modern minimum (1900). We believe that these spikes may be produced by coronal activity of the Sun during the global minima.

4. Interpretation of the Results

It is known from archeomagnetism that the old magnetic structures make a significant contribution to the confidence interval value, because most of them are not completely destroyed after heating of the sample (see e.g. Shcherbakov, McClelland, and Shcherbakova, 1993). The level of demagnetization depends mainly on two factors: the temperature and the electromagnetic oscillation power. Both of these factors have nearly the same effect on the behaviour of domains and multi-domains (MD) (Hill, Gratton, and Shaw, 2002), which are the components of the archaeological thermo-magnetized samples. The temperature dependence is taken into account in the basic Thellier method, when demagnetization curves are built for the sample in the laboratory. In this way the electromagnetic oscillation power could be one of the most significant demagnetization factor which is not compensated by standard measurement procedure.

We suppose here that demagnetization of MD grains can be significantly changed by the geomagnetic disturbances applied to these grains near their unblocking temperatures T_{ub}. In order to estimate the sensitivity of MD grains orientations to small geomagnetic field variations we will consider alternative field (AF) demagnetization by stepwise disturbance which is applied to the sample in narrow temperature range.

Dunlop and Özdemir (2001) have experimentally studied this problem for large AF 3–10 mT. They found that about 50–90% of the remanence unblocks when AF is applied during cooling from 370 to 350 °C. We need to estimate the effect of the much smaller 100 nT AF which is typical for geomagnetic disturbances. Several MD theories are developed up to now on the basis of the domain wall motion description (see e.g. Dunlop and Xu (1994), Xu and Dunlop (1994)). Compared with the simpler Neel's theory of SD grain relaxation these theories can describe some specific effects of MD grains behavior but they contain more parameters which are difficult to estimate in a unique way. So, we will use here elements of Neel's theory evaluated by Tanaka (1999) with corrected parameters for MD grains from Dunlop and Özdemir (2001).

It is known (Dunlop and Xu, 1994) that magnetite MD grains have much smaller coercivity at a room temperature (Hc $\simeq$ 2 mT) instead of 100 mT for SD grains and a broad spectrum of unblocking temperatures. Following Tanaka (1999) we can estimate the remanence fraction for AF field Hb demagnetization as:

$$p = \tanh\left[\frac{\mu v J_S}{kT}\left(1 - \frac{\text{Hb}}{\text{Hc}}\right)h\right], \tag{2}$$

where $h \simeq 40\,000$ nT is geomagnetic field, v is grain volume. Saturation magnetization J_S and coercivity Hc are taken at room temperature ($T_0 = 20\,^\circ$C) for routine AF demagnetization without heating. We shall use J_S and Hc at the MD blocking temperature. Values k and μ are Boltzman's constant and the magnetic permeability in a vacuum, respectively. The thermoremanent magnetization (TRM) remanence fraction has a similar form to Equation (2):

$$p_T = \tanh\left[\frac{\mu v J_S(T_b)}{kT_b}h\right], \tag{3}$$

where T_b is a blocking temperature, saturation and coercivity are temperature dependent in the following way:

$$J_S(T) = J_{S0}\sqrt{\frac{T_C - T}{T_C - T_0}}, \tag{4}$$

$$H_C(T) = H_{C0}\sqrt{\frac{T_C - T}{T_C - T_0}}, \tag{5}$$

where T_C is the Curie temperature of SD grains magnetite, $J_{S0} = 4.8 \times 10^5$ A m^{-1} is taken from Tanaka (1999) as for SD grains, it should be much smaller for MD grains but it does not change the ratio p/p_T because of $\tanh(x) \simeq x$ for such a small x. Grain volume $v \simeq 10^{-17}$ cm^3 also does not influence the ratio. Further we evaluate for MD grains $T_C = T_{ub}$, $T = T_b$ in Equations (4) and (5) and $T_{ub} - T_b = 0.001\,^\circ$C. For the average case (Dunlop and Özdemir, 2001) $T_{ub} \simeq 370\,^\circ$C. In such case, we found $p/p_T = 0.97$ for Hb $= 100$ nT and $p/p_T = 0.86$ for Hb $= 500$ nT. So we found that a geomagnetic disturbance Hb applied during cooling of the archeomagnetic sample in a surrounding geomagnetic field h can lead to 10% better demagnetization (remanence p) compared with only temperature demagnetization (remanence p_T). The effect is due to decreasing coercivity of MD grains at high temperature. We believe that the major part of the broad MD blocking temperature spectrum will integrate this effect during the cooling of the sample.

5. Conclusions

The confidence interval of the archaeomagnetic measurements seems to be dependent on the high-frequency variations in the surrounding geomagnetic field caused by solar activity. It is found that the calculated value Mα_{95} correctly describes the main features of the solar activity secular variation during the years 1500–2000 and so it may serve as a new solar activity proxy. Comparison of new proxy with other available proxies allows us to define more precise positions of global solar activity minima and maxima.

Acknowledgements

The work was supported by grants INTAS 2001–0550 "The solar-terrestrial climate link in the past millennia and its influence on future climate", Federal Scientific and Technical Program "Astronomy-1105", Program of Presidium of Russian Academy of Sciences "Non-stationary phenomena in astronomy", and Russian Fund for Basic Researches No 03-02-17505, 04-02-17560.

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