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Solar modulation of the galactic cosmic ray spectra since the Maunder minimum

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Abstract. Investigations on the galactic cosmic ray (GCR) flux in the past centuries are important for understanding the heliospheric modulation effects during prolonged solar quiet periods like the Gleissberg minima and the Maunder minimum of solar activity. We inferred the GCR annual mean spectra on the basis of the following data: primary spectra of cosmic rays obtained from balloon and spacecraft measurements during different phases of the solar cycles # 20-23; the Climax neutron monitor time series available since 1953; variation of the annual means of the coronal source magnetic flux as derived from the *aa* index available since 1868 and of the evolution of the Sun's large scale magnetic field; the sunspot number time series from 1600. The differential flux of the galactic cosmic ray $J_G(T,M)$ (particles/m^2 s sr MeV) has been characterized by the parameter M (MeV), the energy lost by particles in traversing the heliosphere, which depends on the modulation by the solar magnetic field. The relations among these data sets were extrapolated back to 1700.

1 Introduction

The GCR flux modulated by the solar activity and measured at 1 AU shows well established periodicities from days to decades. The 11 year cycle, in addition to the direct measurement of primary and secondary cosmic rays, is clearly shown by the cosmogenic ^{22}Na ($T_{½}$=2.6 yr) in meteorites which fell in the last decades (Evans et al., 1982; Bhandari et al., 1994; Bonino et al., 1997) and by ^{10}Be measured in Greenland ice core (Beer et al., 1990). All these measurements show a clear anticorrelation between the GCR flux and the sunspot number R series.

A century scale modulation (Gleissberg cycle), expected by the R series, has been shown in the cosmogenic ^{44}Ti ($T_{½}$=59.2 yr) activity measured in meteorites which fell in the last two centuries (Bonino et al., 1995; 1999) and in the time series of ^{14}C in tree rings (e.g. Damon and Sonett, 1991).

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The century scale modulation of GCR recorded both in meteorites and in terrestrial archives shows that during prolonged solar quiet periods, like the Gleissberg minima, the cosmogenic radionuclide concentrations were higher than during the short lasting recent decadal minima. In terrestrial archives these concentrations may be also controlled by Earth’s effects such as deposition rate variations of the ^{10}Be in ice cores, carbon cycle variations for ^{14}C, etc., while in meteorites, being produced in space, they are free from terrestrial influences.

We observed that the ^{44}Ti variations from century minima and maxima are about four time higher than calculated on the basis of the GCR flux measured in the last decades and extrapolated in the past simply on the basis of the sunspot number (Bonino et al., 1995; 1999).

We present here a different procedure for the calculation of the GCR spectra based on the annual mean of the coronal source magnetic flux as derived from the *aa* index (Lockwood et al., 1999) and of the evolution of the Sun’s large scale magnetic field (Solanki et al., 2000). The calculated GCR flux, extrapolated back to 1700, can be validated with our measurements of the ^{44}Ti activity in meteorites which fell in the last two centuries.

2 GCR Spectra and the solar modulation parameter

Comparison of the sunspot number R with the Climax neutron monitor counting rate, available since 1953, shows an anticorrelation between the two time series. However it is also known that the solar modulation processes are more complex than a simple anticorrelation with the solar activity indexed by some parameter like R. The modulation is larger at lower GCR energies and has little influence on high energy particles (> 10 GeV/n).

The modulation of GCR as a function of position, energy and time in the heliosphere is a complex combination of different mechanism (e.g. Jokipii, 1991; Potgieter, 1993). Models of the inward transport of GCR have been successful. However, because of the complexity of the modulation dynamics they do not allow to determine unambiguously the GCR fluxes for any solar activity cycle.

We have to look at a theoretical model which gives a good fit with the observed modulation at different energies and for different solar cycles. Cini Castagnoli and Lal (1980) adopted the force field approximate solution of the transport equation as given by Urch and Gleason (1972). The differential flux $J_G(T,M)$ (particles/m^2 s sr MeV) of protons is given in terms of the solar modulation parameter M:

$$J_G(T,M) = 9.9 \cdot 10^8 \frac{T(T+2E_0)}{(T+M)} \cdot \frac{(T+M+780 \cdot \exp(-2.5 \cdot 10^{-4} T))^{-2.65}}{(T+M+2E_0)} \quad (1)$$

where T is the kinetic energy per nucleon and E_0 is the rest energy of a nucleon.

Since solar cycle 20, several balloon and spacecraft observations of GCR protons are available. We considered here 29 experimental spectra covering the time interval 1963-1998 for our calculations. For each experiment we have obtained the corresponding solar modulation parameter M from the best fit of the experimental $J_G(T)$ with Eq. (1).

Fig. 1 shows some comparison of the fitted J_G spectra with the experimental values, obtained in 1965 (Ormes and Webber 1968), 1968 (Hsieh et al., 1971), 1980 (Kroeger, 1986), 1989 (Webber et al., 1991) and giving M =390, 600, 820, 1080 MeV, respectively. We can observe a quite good agreement between measured and calculated J_G.

3. Extrapolation of the GCR spectra

In previous papers (Bhandari et al., 1989; Bonino et al., 1995) we have calculated $J_G(t)$ over the last two centuries with the following procedure. The polynomial regression between the Climax neutron monitor count rate $N_m(t)$ and the annual sunspot number, R, for the period 1953 to 1992 was extrapolated back to 1750 from R(t). $J_G(t)$ was then calculated by a linear regression between Climax neutron monitor count rates normalized to that of January 1965 (4291.7 counts/h*100=1) and balloons measurements of GCR protons during solar cycles 20 and 21. $J_G(t)$ extrapolated to 1750 was utilized for calculation of the expected activity of the cosmogenic ^{44}Ti in meteorites by means of isotope production model. Although the calculated absolute activity may be model dependent, its variation is function of $J_G(t)$. We compared the calculate profile with the ^{44}Ti activity measured by us in several chondrites which fell in the last 160 years. We observed that the phase of the measured profile agreed with that expected, but the amplitude of the secular excursions was about four time higher then calculated. We deduced that during prolonged solar minima, such as Dalton and Modern minima, the heliosphere admitted a higher GCR flux compared to that deduced from observations in the last decades and extrapolated in the past, solely by sunspot number R(t), following the procedure reported above (Bonino et al., 1995; 1999).

We evaluate here the GCR spectra in the past on the basis

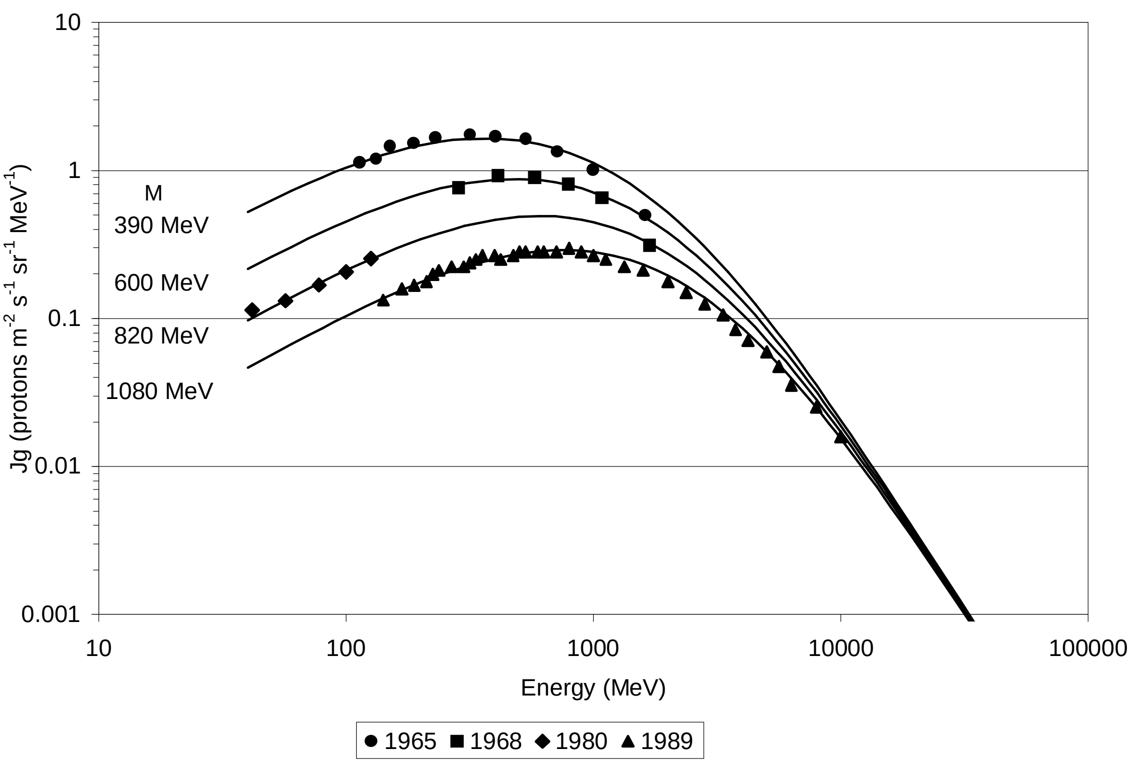

Fig. 1. Differential cosmic-ray spectra obtained from Eq. (1) for different values of the solar modulation parameter M = 390, 600, 820, 1080 MeV corresponding to the measurements performed with balloons or spacecrafts during 1965, 1968, 1980 and 1989 respectively.

of the recent evaluation of the Sun's magnetic field since 1700 and following the procedure reported below.

Lockwood et al. (1999) showed that the solar magnetic flux emanating through the coronal source, as derived from the *aa* geomagnetic index available since 1868, has about doubled in the past 100 years. Solanki et al. (2000) developed a model describing the long-term evolution of the Sun's large-scale magnetic field, ϕ_0, which reproduces the doubling of the interplanetary field and evaluated the evolution of ϕ_0 since 1700.

On the basis of these new results and following basically our procedure reported above we have calculated the GCR spectra until 1700. From a linear regression between the Climax N_m and ϕ_0 (since 1953) and a quadratic regression between the solar modulation parameter M and the normalized N_m* for the years of the balloon and spacecrafts measurements of GCR protons (covering the time interval 1963-1998) we deduced $J_G(T,t)$. Then we extrapolated J_G to 1700 on the basis of these regressions and of ϕ_0 given by Solanki et al. (2000). Fig. 2 shows $J_G(t)$ for different ΔT.

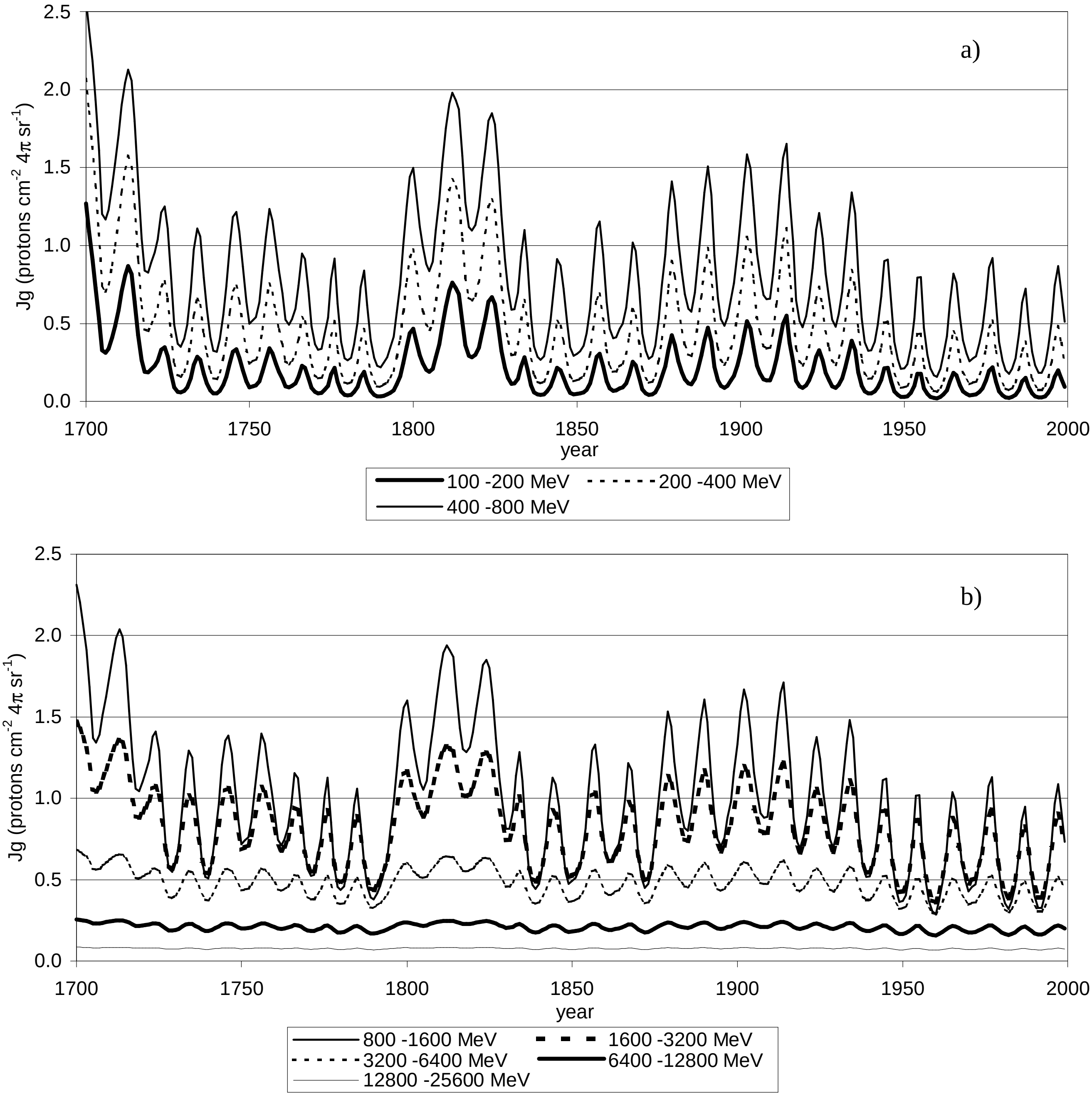

Fig. 2. Proton flux $J_G(t)$: a) for the kinetic energy intervals ΔT = 100-200 MeV, 200-400 MeV, 400-800 MeV; b) for ΔT = 800-1600 MeV, 1600-3200 MeV, 3200-6400 MeV, 6400-12800 MeV, 12800-25600 MeV.

We can observe a broad modulation of GCR for T<10 GeV, depending on the ΔT interval, with larger variations for ΔT = 400-800 MeV and 800-1600 MeV and with negligible variations for ΔT > 10 GeV, as expected.

The most prominent result concerns the J_G flux during the prolonged solar quiet periods. We deduce that around 1700 (in the final pulse of the Maunder minimum), during the Dalton minimum (~1800) and the Modern minimum (~1900) J_G was much higher (about 3 times) respect to J_G observed in the last decades. This confirms our previous results based on our measurements of the cosmogenic radioisotope ^{44}Ti in meteorites which fell in the last two centuries (Bonino et al., 1995; 1999). Furthermore, utilizing $J_G(T,t)$ as deduced here, for model calculation of the ^{44}Ti profile (taking into account the experimental cross section of the nuclear interaction of GCR with the main target element Fe, Ni, and Ti for isotope production (Michel and Neumann, 1998)) we obtain a good agreement with our experimental data (Bonino et al., in preparation). This result constitutes a good validation of our estimation of the GCR spectra evolution since 1700.

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