29th International Cosmic Ray Conference Pune (2005) **2**, 195-198

Heliospheric modulation of cosmic rays based on ^{44}Ti produced in stony meteorites over the past 250 years

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^{44}Ti (half-life 59.2 years), produced by spallation reactions of Galactic Cosmic Rays (GCR) in meteorites, provides information about the GCR flux in the past and allows estimation of the modulation effects of the Sun between about 1 to 3 AU on the centennial time scale. We have measured ^{44}Ti in 18 meteorites that fell since 1760 on an efficient and selective hyperpure Ge+NaI(Tl) coincidence γ-ray spectrometer system set up in the Laboratory of Monte dei Cappuccini in Torino. Although the errors in the measured ^{44}Ti activity are large, particularly for old meteorite falls, the results can be understood in terms of a centennial cycle with an amplitude of ~20% (peak to trough) and a linear trend of decreasing ^{44}Ti-activity. The results imply a decrease of GCR flux, of about 1% per decade, over the past 250 years, superimposed on the Gleissberg cycle. In order to confirm the very low activity of ^{44}Ti in meteorites fallen before 1850, we have recently set up a new spectrometer with higher efficiency and resolution. The background is thus reduced by a factor of ~2 in the ^{44}Ti-region. Measurements on some meteorites on the new spectrometer confirm our previous results. Study of very old falls to confirm the long-term trend is now in progress.

1. Introduction

The most important proxies of solar activity variations in the past are the radionuclides produced by nuclear interactions of galactic cosmic rays (GCR) in Earth's atmosphere, in meteorites and in planetary surfaces. The production rate of these nuclides [1,2] depends on the GCR flux and energy spectrum which, in turn, are controlled by variations in the heliospheric magnetic field.

The concentration of radioisotopes produced in the atmosphere and subsequently deposited in terrestrial archives (such as ^{10}Be in ice cores and ^{14}C in tree rings) is significantly influenced by climatic processes. For example, precipitation rate and temperature affect ^{10}Be deposition rate and exchange between various terrestrial reservoirs affect ^{14}C activity. In comparison the variations of the radionuclides concentration in meteorites relate only to cosmic ray flux in the interplanetary space and are free of terrestrial influence. To understand the behaviour of GCR in the interplanetary space, we have measured ^{44}Ti in stony meteorites. The half life of 59.2 years makes ^{44}Ti suitable for studying the century scale modulation of the GCR flux by heliospheric magnetic field variations.

2. Experimental apparatus

The activity level of ^{44}Ti in meteorites is low (~1 dpm/Kg); moreover its detection is difficult due to the strong interference from the γ-activity of the ubiquitous naturally occurring ^{214}Bi. In order to overcome these obstacles, we have set-up a selective and sensitive γ-ray spectrometer [3,4], specially tailored for measurement of 1157 KeV ^{44}Ti (^{44}Sc) decay gamma rays. The main detector is a high-purity large Ge diode (~2 kg), with high resolution and efficiency, surrounded by an active shield of NaI (Tl) (~30 kg), allowing high selectivity for decays by positron emission, resulting in annihilation γ-rays. The passive shield consists of 20 cm thick high-purity lead and 3 cm OFHC (Oxygen Free High Conductivity) copper.

In order to reduce the ambient radon level, N_2 gas is flushed in the space between Ge and NaI detectors. This apparatus is housed in the underground (70 m.w.e.) Laboratory of Monte dei Cappuccini in Torino.

This system has shown high degree of stability, both in energy and counting rate over long periods of time, making it suitable for performing measurements of meteorites lasting for several months.

3. Measured meteorites

In Table 1 we give the details of 18 meteorites measured using the experimental apparatus described above. These meteorites fell during 1766 to 1996, covering a period of 230 years.

Table 1. The 18 measured meteorites

Meteorite	Group	Date of fall	Recovered mass (kg)	Weight of sample (g)
Albareto	LL4	July 1766	2	580
Mooresfort	H5	August 1810	3.5	1145
Charsonville	H5	23/11/1810	27	524
Agen	H5	5/9/1814	30	683
Cereseto	H5	17/7/1840	6.46	1308
Grueneberg	H4	22/3/1841	1	717
Kernouve'	H6	22/5/1869	80	820
Alfianello	L6	16/2/1883	228	625
Bath	H4	29/8/1892	21	539
Lancon	H6	20/6/1897	7	1080
Holbrook	L6	19/7/1912	220	331
Olivenza	LL5	19/6/1924	150	247.4
Rio Negro	L4	21/9/1934	1.31	388
Monze	L6	5/10/1950	unknown	165
Dhajala	H3	28/1/1976	45	706
Torino	H6	19/5/1988	0.977	445
Mbale A	L5	14/8/1992	150	700
Mbale T				730
Fermo	H3	25/9/1996	10.2	800

Due to the low activity of ^{44}Ti, the counting of each meteorite was carried out for a period of 4 to 12 weeks in order to have suitable statistics.

4. ^{44}Ti activity and long-term GCR modulation

The ^{44}Ti activities for all the meteorites (Table 1) are plotted in Figure 1 as a function of their time of fall. Since ^{44}Ti is a spallogenic product, formed mainly from Fe and Ni in meteorites, the activities are normalized to (Fe+Ni) concentrations in each chondrite. As the production of cosmogenic radioisotopes in meteorites depends on the size of the meteoroid in space and on the effective shielding depth of the fragment measured, suitable shielding corrections were made on the basis of track density produced by CR heavy nuclei, following the procedure of [5]. The activity at the time of fall was calculated on the basis of the value of $T_{1/2}$ = 59.2 years, determined in our laboratory in collaboration with laboratories at Argonne and Jerusalem [6].

Although the time series analysis is limited because of small number of points, in order to determine any trends or regularities in the data, we use the Singular Spectrum Analysis (SSA; described in Appendix 1). Before performing this analysis, in order to improve the errors we have averaged the activities of meteorites fallen during the same period (Agen-Mooresfort-Charsoville and Cereseto-Grueneberg) and we have interpolated the data at 5 years sampling interval. We find that RCs 1,4 capture the long-term trend (light curve in Figure 1) and RCs 2,3 describe a centennial oscillation. In Figure 1 the series reconstructed from RCs 1 to 4 is also shown (heavy curve).

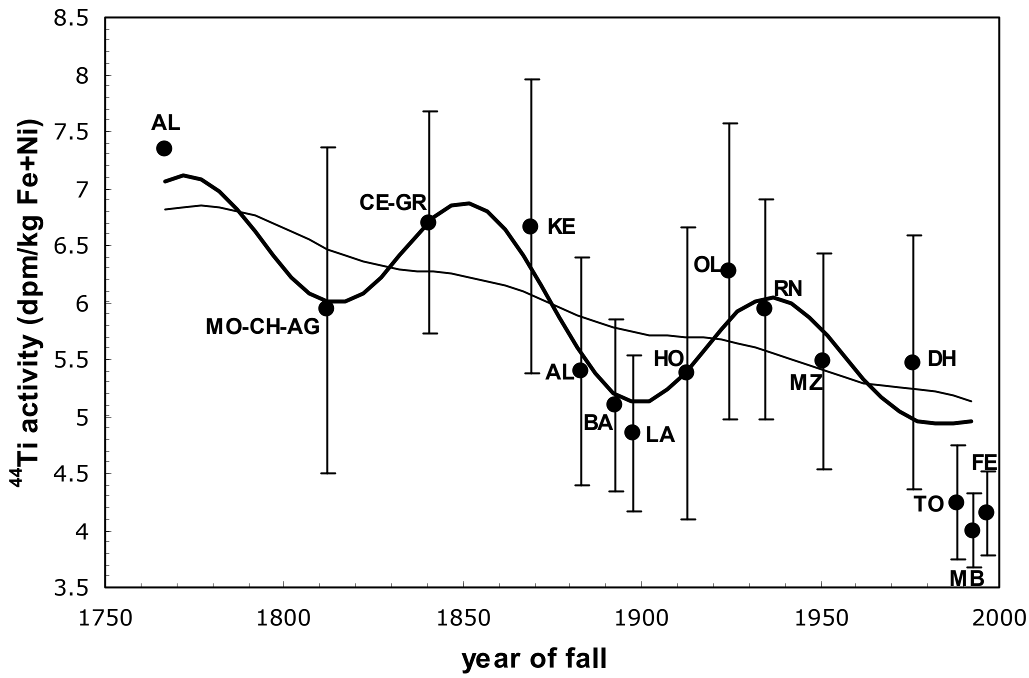

Figure 1. ^{44}Ti activity measured in chondrites: Charsonville (CH), Agen (AG), Cereseto (CE), Grueneberg (GR), Kernouve' (KE), Alfianello (AL), Bath (BA), Lancon (LA), Holbrook (HO), Olivenza (OL), Rio Negro (RN), Monze (MZ), Dhajala (DH), Torino (TO), Mbale (MB), Fermo (FE). Superimposed on the data, we show the SSA reconstruction by RCs 1 to 4 (heavy curve) and by RCs 1,4 (light curve). For this analysis, we used a window width M=23 (corresponding to 115 years).

This analysis shows a linearly decreasing trend of ~27% in ^{44}Ti activity and hence of GCR flux during the past 230 years, superimposed on an oscillation with a periodicity of about 100 years with a peak to trough amplitude of ~20%. The Gleissberg solar cycle with a periodicity of about a century is well known. The periodicity in ^{44}Ti activity has a phase lag of about 40 years in comparison to the Gleissberg cycle, as expected for an isotope of 59.2 year half-life. We therefore attribute the centennial scale oscillation to the influence of the Gleissberg solar cycle. We are now able to calculate the amplitude of the Gleissberg cycle from the meteorites of Table 1.

5. Conclusions

We have shown that the ^{44}Ti activity in 18 chondrites that fell during 1766 to 1996 reveals a cyclic variation with a period of about 100 years and with an amplitude of ~20% (peak to trough) and a linear trend of decreasing activity (~27% over 230 years). In order to confirm the low activity of ^{44}Ti in meteorites which fell before 1850, we have recently set up a new spectrometer with higher efficiency and resolution. The background is reduced by a factor of ~2 in the ^{44}Ti energy region. The measurement of the Albareto meteorite using this new spectrometer is now in progress, to determine more precisely the long-term trend.

6. Acknowledgements

This paper is dedicated to the memory of Prof. G. Cini Castagnoli and Prof. G. Bonino for their careful and ceaseless efforts over many decades, without which this study would not have been possible and to Prof. Carlo Castagnoli for his continuous guidance and encouragement.

Appendix 1

The SSA approach [7] involves three basic steps: 1) embedding the time series in a vector space of dimension M; 2) computing the MxM lag-covariance matrix $\tilde{C}_D$ of the data; 3) diagonalizing $\tilde{C}_D$: $\Lambda_D = E_D^T \tilde{C}_D E_D$, where $\Lambda_D = diag(\lambda_1, \lambda_2, \ldots, \lambda_M)$, with $\lambda_1 \geq \lambda_2 \geq \ldots \geq \lambda_M \geq 0$ and E_D is the MxM matrix having the corresponding eigenvectors E_k , k=1,...,M as its columns. For each E_k we construct the time series (of lenght N-M+1), called k-th principal component (PC), representing the projection of the original time series in the direction determined by the eigenvector E_k (also called empirical orthogonal function, EOF). Each eigenvalue λ_k gives the variance of the corresponding PC; its square root is called singular value. Choosing a subset of eigenvalues, it is possible to extract time series of length N, combining PCs; these time series are called reconstructed components (RCs) and they can be superimposed on the original signal.

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