

## Cosmic ray intensity for about five solar cycles

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**Abstract.** Continuous records of the cosmic ray nucleonic component have been achieved at Rome (SVIRCO Group) by using data from different types and locations of neutron monitors (first at La Sapienza University: 41.90°N, 12.52°E, altitude about 60 m a.s.l., and then at Roma Tre University: 41.86°N, 12.47°E, about sea level). The normalized data, covering the whole period from July 1957 to June 2014, are available to the scientific community by simple request. Here we illustrate some useful results derived from them.

### 1. Introduction

The Cosmic Ray (CR) Physics has been developed until about 1955 by using terrestrial measurements in specific research projects (mainly mini-networks of ionization chambers, balloons, ship and aircraft surveys). Only after the start of the Geophysical International Year (1957-1958) and the Space Age the field was world-wide faced. The last five decades gave considerable progress towards the understanding of the solar wind/CR relationship through the study of solar wind macrostructures and wind turbulence in the heliosphere. On the other hand, with the improvement of our knowledge on the terrestrial atmosphere and magnetospheric physics (thanks to satellite measurements), it was possible to quantitatively describe atmospheric and geomagnetic effects on CRs arriving at the different locations of the Earth.

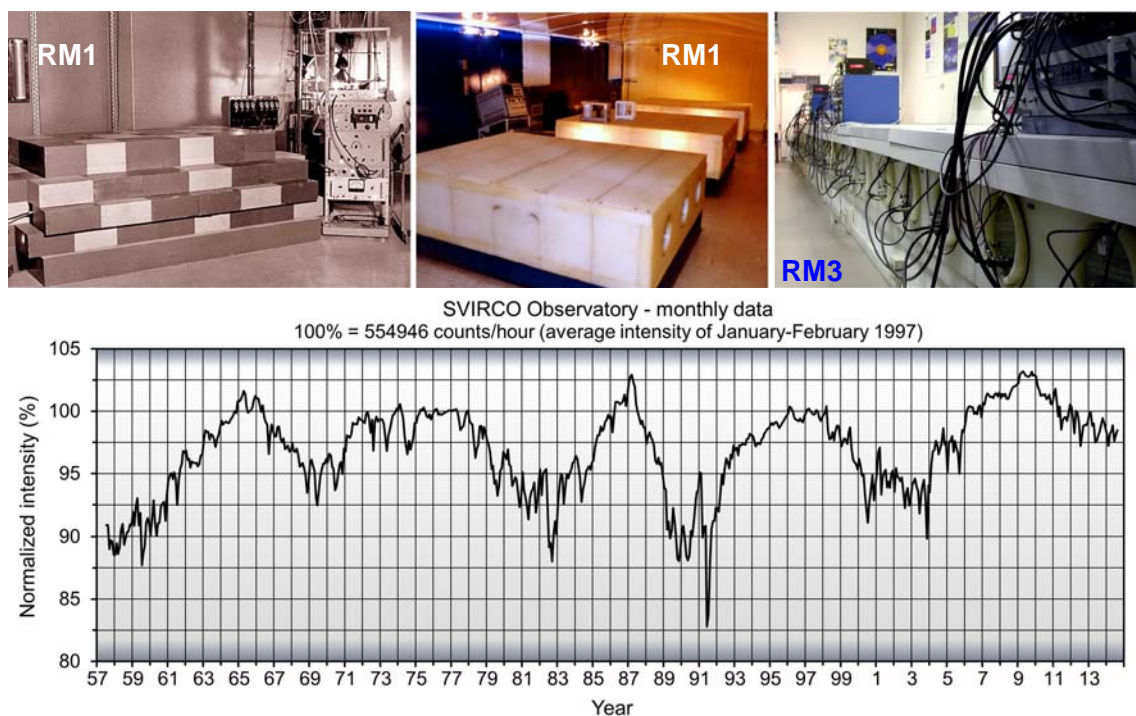
A remarkable synergy between CR studies and space measurements led to investigate in detail CR variations such as the 11-yr (22-yr) modulation, 27-day recurrences, Forbush decreases, CR anisotropies, solar energetic particle (the so-called SEP/GLE) events. The possibility to extend the research at low CR energies in the interplanetary space not only helped the investigation of SEP events but also brought to the discovery of relevant heliospheric phenomena related to CR physics (e.g. charged particle/shock interactions, creation/propagation of pick-up ions and anomalous CRs, corotating ions, 3D-transport of charged particles). Nevertheless, along with the great amount of information obtained from space missions, ground-based instrumentations (ionization chambers, Geiger-Muller counters, neutron monitors, muon telescopes, air shower arrays,...) continue to be required for many research works, particularly for the new scientific branches of the dynamical heliospheric environment. There exist many links between such branches and CRs; for example, it is possible to use CR signatures to forecast/nowcast Space Weather events, to rebuilt Space Climate data series or to help International Alert Services for the so-called dangerous events (including the ones directly connected with the CR interaction with matter such as the biological tissues).



In other words, research during this century still needs continuous CR records but with high-temporal resolution and low statistical errors (as underlined by [1]). In this context, efforts have been made at Rome (Italy) to maintain a *long data series of homogenous CR intensities* derived from measurements performed with different types and locations of neutron monitors (see section 2). The neutron monitor (NM) data has been employed over the years to investigate several research topics by using different mathematical tools, such as the Descriptive Statistics (DS [2]; subsection 2.1), the Wavelet Technique (WT [3]; subsection 2.2), or the Empirical Mode Decomposition (EMD [4]; subsection 2.3). We discuss some results (section 3) to emphasize the relevance of a homogeneous CR dataset for Space Research.

## 2. SVIRCO Observatory and Terrestrial Physics Laboratory of Rome

A research team, aiming to investigate cosmic ray intensity variations (Italian acronym: SVIRCO), was formed at the start of the second half of the last century in Rome (see [5] for details). The SVIRCO station (now observatory) for continuous measurements of the nucleonic component was opened on 1 July 1957 with the so-called IGY neutron monitor (figure 1, left upper panel) at the Physics Department of La Sapienza University (RM1: 41.90°N, 12.52°E, altitude 60 m a.s.l.). It was replaced with a NM-64 type during 1966 (figure 1, middle upper panel). In May 1997 the NM-64 was moved into the Physics Department of Roma Tre University (RM3: 41.86°N, 12.47°E, altitude about s.l.; see right upper panel of figure 1). Since then it has been continuously running at the new location (<http://webusers.fis.uniroma3.it/svirco/>).



**Figure 1.** *Upper panel:* La Sapienza University (RM1: IGY detector, left; NM-64, center) and Roma Tre University (RM3: NM-64, right). *Lower panel:* Monthly averages of the nucleonic component as derived from Rome experimental data for the July 1957 to June 2014 time interval.

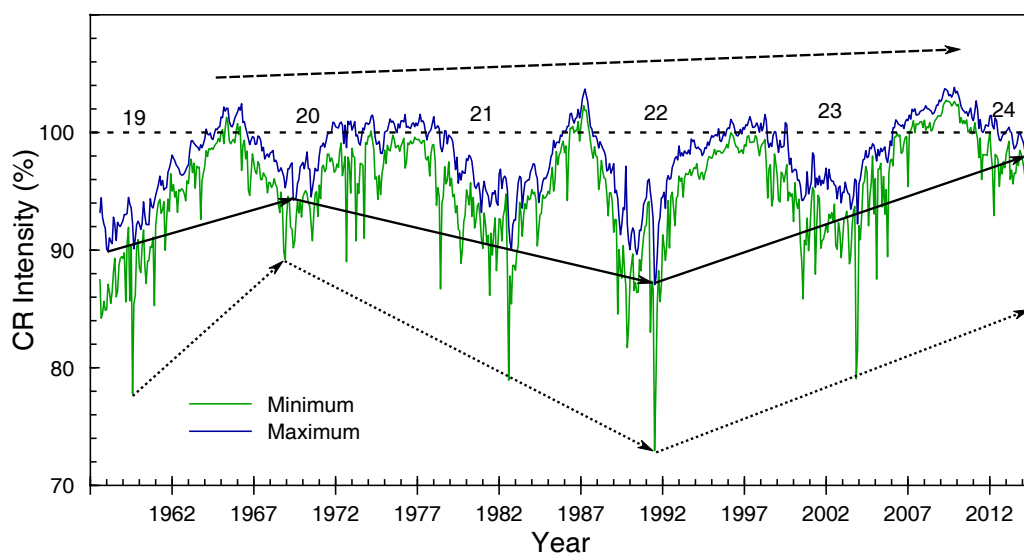
Different detector configurations were used over the years (see table 1 reported by [5]).

Annual data reports are made available to the scientific community by using revised hourly, daily and monthly records (e.g. [6] and references therein). Moreover, monthly prompt reports with 5-min data are published since 2003. Also efforts to evaluate the diurnal wave at Rome are performed and results are published as soon as they are ready (see [7] as an example).

Particular attention was paid to create a homogeneous dataset on hourly, daily and monthly basis (we will call it RM set) for long term studies. As an example, the lower panel of figure 1 shows the monthly averages obtained for July 1957 - June 2014.

### 2.1. DS of Rome CR data

Descriptive Statistics (DS, [2]) was used during the nineties to investigate general aspects of CR modulation. In fact, DS allows to characterize a data set in general terms such as mean, variance, standard deviation, extreme values, skewness, kurtosis, and so on. The monthly means and the associated parameters, derived from the homogenous RM set, allowed correctly to follow the CR modulation from one solar activity cycle to the next and to identify difference between even and odd cycles. It was also possible to confirm the existence of the Gnevyshev Gap (identified in the polar neutron monitor records by [8]) in the time history of a middle latitude measurement site [9].



**Figure 2.** Monthly extreme values of the nucleonic component of galactic cosmic rays derived from the RM set on daily basis. See the text for arrows meaning.

The lower panel of figure 1 (where the 100% of intensity was arbitrary fixed as the average value derived from January-February 1997 pressure corrected data) shows that the CR modulation level is practically the same during the transition from an even to an odd solar activity cycle (i.e. 20/21 and 22/23). On the contrary, transitions from odd to even cycles demonstrate a tendency for decreasing levels of modulation (19/20 → 21/22 → 23/24). Such features are better seen in figure 2 where extreme daily values inside each monthly data subset were selected. Briefly, DS analysis suggests:

- equivalent intensity during the plateau phases of CR modulation.
- an effective residual difference between maximum and minimum daily intensity levels.
- a tendency for a slow increase of RM intensity at the end of odd modulation cycles, from cycle 19 to 23 (see dashed line).
- periodicities higher than the one of the Schwabe cycle (as continuous and dotted arrows underline).

The study of solar periodicity transmission in the heliospheric environment deserves special attention. From such kind of study it is possible not only to separate fundamental periods from the harmonics but also to investigate phenomena associated with CR modulation behaviour. Certainly, more cycles covered by continuous CR records will help to decide if Sun exhibits a quasi-periodic (stochastic) or intermittent (deterministic chaos) behaviour, but presently some insight into the matter can at least be reached.

## 2.2. *WT on Rome CR data*

The Wavelet Transform (WT, [3]) is generally used to investigate the time evolution of periodic or quasi-periodic trends of experimental data sets (e.g. [10] and [11] for details). It allows to analyze non-stationary processes containing multi-scale features. In fact, the technique is able to determine both the dominant variability modes and how those modes vary in time, by decomposing a time series into the time-frequency space.

The possibility to evaluate a local spectrum by means of the WT distinguishes the wavelet analysis from the different Fourier approaches or mathematical filtering techniques. Main periodicities such as quasi-annual, quasi-biennial, about a decade and about two decades were identified in the RM set of monthly averages covering 1957-2004 and discussed within the heliospheric context (see, among others, [12] and [13]).

Presently, it is very interesting to study the 5-minute averages of the RM dataset. The analysis of the 10 September 2005 Forbush decrease (FD) has suggested that such kind of fine data resolution contains a signal for interplanetary storms approaching the Earth up to 9 hours before the onset of the main phase of the event [14]. This is a feature related to the CR 3D-propagation in the inner heliosphere (as underlined in the last section of this paper), that can be easily observed by analysing the time behaviour of the 8-h CR periodicity derived from data recorded by a single detector with near equatorial particle asymptotic directions and the systematic use of the WT code (available at <http://paos.colorado.edu/research/wavelet>). The exploitation of this method, described in detail by [14], should be useful for Space Weather purposes.

Also Space Climate can take advantage from long time series of CR measurements. For example, to create lists of homogenous interplanetary plasma streams it is possible to apply the WT code on the 5-minute averages of the RM set and search for periodicities in the range 24 h to 120 h. Figure 3 exemplifies in its upper panel (including four graphs) results for two consecutive transient solar wind streams (**TS-1** and **TS-2**) observed during May 2005. They produce two intense Forbush decreases (**FD-1** and **FD-2**, of about 4 % each one). Three CR periodicities (24 h, 55 h and 74 h) were identified evaluating significant peaks in the global WT power spectra against a white noise background at the 95% statistical confidence level.

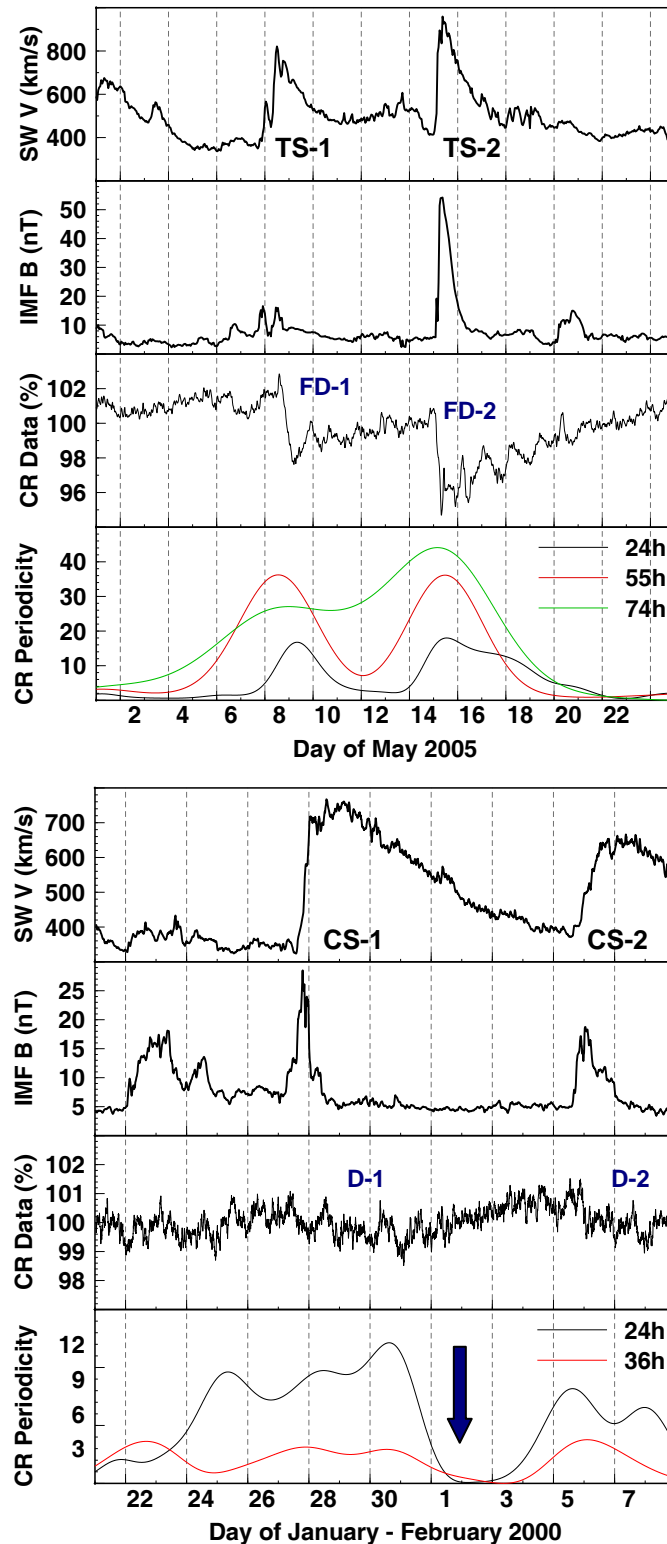
The fourth graph of the upper panel of Figure 3 illustrates for each periodicity the time history of the power/noise signal ( $R$ ). Assuming a ratio  $R \geq 5$  it is possible to observe that such signal starts to be significant before the beginning of the CR event and cover at least the complete Forbush decrease phenomenon. This is particularly true if the high periodicities (55 h and 74 h) are considered. It is interesting to notice that for the 74 h periodicity the  $R$  trend never decreases to no significant levels.

Figure 3 also reports in its lower panel results obtained by analyzing the 21 January – 8 February 2000 period, characterized by corotating plasma streams (**CS-1** and **CS-2**) in the near Earth space. In this case the solar wind perturbations are causing small or moderate CR decreases (**D-1** and **D-2**); only the 24 h and 36 h periodicities were singled out, imposing the above significance level for peaks in the global WT power spectra.

The range of variability for the power/noise signals (fourth graph of the lower panel of figure 3) resulted to be small for corotating streams if compared with those obtained for transient streams (fourth graph of the upper panel). Setting again the threshold of  $R \geq 5$  for the power/noise of periodicities only the 24 h signal is significant, even before the stream arrival in the near Earth space and its time history is consistent with past results for the diurnal wave [15]. In fact, during the transit of the trailing edge of the corotating stream the periodicity signal went to zero significance (see the arrow shown in the fourth graph of the lower panel).

Comparing the  $R$  time history of May 2005 with the one of January-February 2000 for the identified periodicities, we conclude that transient and corotating stream effects on CRs are very different and can be inferred from CR records.

The described features should help to discriminate the passage in the near-Earth space of transient from corotating solar-wind streams, particularly when no interplanetary data are available.



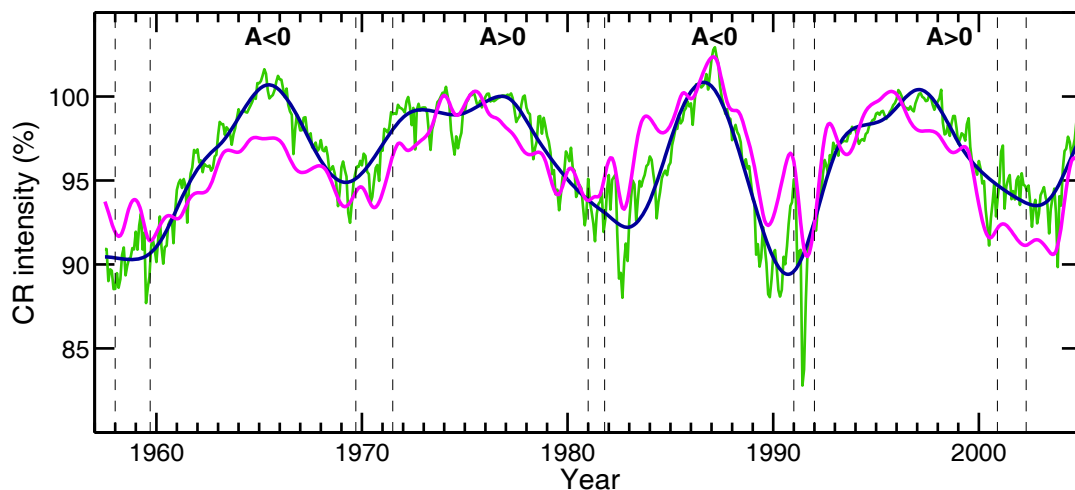
**Figure 3.** Power to noise of CR periodicity, percentile of the CR variability, interplanetary magnetic field (IMF) intensity B and solar wind (SW) velocity V (as measured in the near-Earth space: <http://omniweb.gsfc.nasa.gov/>) for transient (*upper panel*) and corotating (*lower panel*) interplanetary perturbations.

### 2.3. EMD for Rome CR data

The variability of the monthly RM set, covering 1957-2004, was also analyzed through the Empirical Mode Decomposition (EMD, [4]) analysis, which is a proper method for the description of non-linear and non-stationary processes containing multiscale features. It is a mathematical tool able to split a dataset into a finite number of components (called intrinsic mode functions), representing  $C_j$  oscillatory modes in the time domain, with the signal described by a time dependent amplitude and phase function.

We identified the significant periodicities (through the  $C_j$  modes) in the RM set (and their relative amplitude) by deriving the eigenmodes from the signal without a priori conditions. Several interesting results, able to connect CR modulation phenomena with the heliospheric environment, were obtained (in particular we highlight results discussed in papers [16] to [20]; see figure 2 reported by [18] for  $C_j$  significance test). Briefly:

- (i) the  $C_3$  (typical period:  $1.02 \pm 0.02$  yr) mode is related to the annual variation.
- (ii) the  $C_4$  ( $1.6 \pm 0.1$  yr) mode characterizes Quasi Biennial Oscillations (QBOs) during 1965-1976 and 1987-1995 (i.e. during even solar cycles) and the  $C_5$  (typical period:  $2.7 \pm 0.1$  yr) mode during 1978-1986 and 1995-2004 (odd solar cycles).
- (iii) the QBO contribution (obtained by summing up modes  $C_4$  and  $C_5$ ) to the global signal is not the same during successive solar cycles, although the amplitude ratio QBO/11 yr is at least 30 % ( $\sim 11$  yr mode identified as  $C_7$ :  $10.4 \pm 0.4$  yr).
- (iv) QBOs of CR data are delayed with respect to sunspot activity but the time lag ( $\tau$ ) is shorter for the positive polarity states of the heliosphere (the so-called  $A > 0$  periods of even sunspot cycles;  $\tau < 5$  months) than for the negative ones ( $A < 0$  periods of odd cycles;  $\tau > 5$  months).
- (v) the superposition of the  $\sim 11$  yr and QBO modes well reproduces the experimental data set during the maximum phase of the Schwabe cycles as can be seen in figure 4 (compare the magenta with the green curve). It also seems to account for the Gnevyshev Gap phenomenon.
- (vi) the observed step-like (medium term) CR modulation can be partly described by the superposition of QBOs to the long-term trend of  $\sim 11$  yr.



**Figure 4.** CR intensity as derived from experimental data recorded at Rome (green line), superposition of the  $\sim 11$  yr and QBOs (magenta line) and superposition of the  $C_6$ ,  $C_7$ , and  $\sim 22$  yr modes (blue line) computed by using EMD. Vertical dashed lines delimit the short time period when there was no well-defined heliomagnetic field polarity.



- (vii) the  $C_6$  ( $5.6 \pm 0.5$  yr) mode is correlated with the heliospheric current sheet (HCS) latitudinal excursion (from the equatorial to polar solar latitudes and vice versa) and its role in charged particle drift phenomena. Nevertheless, a threshold for the HCS tilt angle there exists: over the threshold value the CR flux recorded at a measurement point is unaffected, below the threshold the CR flux is strongly modulated by the tilt angle variations.
- (viii) the  $C_6$  mode also accounts for the flat/peaked CR maximum during even/odd cycles (compare the blue with the green curves reported in figure 4, where a good agreement between experimental data and data reconstruction including  $C_6$  is obtained).

The detailed study of  $C_1$  and  $C_2$  modes will be performed in the future, as the  $C_8$  (or higher) mode which requires a CR set covering more sunspot cycles of data.

### 3. Discussion and conclusion

Space Weather/Climate investigations require complete data series to extract correct features able to characterize phenomena under study. Often proxy data are used for filling procedures aiming to avoid data gaps in the investigated dataset. Among the proxy data used for solar-terrestrial relation studies, CR intensity records were the ones often tested in the past. They resulted to be a relevant tool in such kind of procedures, provided that homogeneous CR datasets are used.

Some results derived from the use of 5-minute, daily and monthly CR intensities of Rome NM are illustrated in section 2. Here we briefly discuss aspects of the heliospheric environment at the origin of the reported CR modulation phenomena.

Inhomogeneous regions of the interplanetary space, such as those present during traveling interplanetary perturbations generated by solar flares and CME ejections are able to change CR paths in the heliosphere; signatures of the moving 3-D structure of transient plasma streams are transferred to the near-Earth space before the stream arrival by the relativistic CRs. Hence, promising results can be obtained by using CR records in forecasting codes, not only by using contemporary hourly data from several CR detectors but also from a single detector if fine time resolution records are used.

Moreover, the CR paths inside/outside the complex plasma structures generate intense periodicities in the terrestrial CR records, which are not present in a quasi-stationary inner heliosphere. This is the case for corotating plasma streams traveling from the Sun to the Earth with stable (or slowly varying) macro structures, able to induce practically only azimuthal CR variability.

The signatures identified by using data with fine time resolution help to discriminate transient from corotating solar-wind streams and to build up lists of homogenous type of interplanetary perturbations even when no in situ data are available.

Medium- and long-term characteristics of CR modulation can be derived from a detailed study of CR periodicities with an appropriate mathematical tool. The use of the EMD on CR records clarified the relevance of QBOs, which are together with the one of the Schwabe cycle the outstanding variabilities present in CR datasets. QBOs seem also to be at the origin of the Gnevyshev Gap and CR step-like phenomena. Moreover, a relationship between the HCS position and the CR flux reaching the terrestrial environment was found.

Due to space limitations we would like only to remark that the obtained results were strengthened by including in most of the investigations other NM data series such as those recorded at:

- Climax and Huancayo/Haleakala: [12-13] and [18-20];
- Calgary, Climax, Lomnický Štít and Huancayo/Haleakala: [21];
- Lomnický Štít and LARC: [22].

These locations have different rigidity thresholds and they offer the possibility to look for the energy dependence of the investigated phenomena.

The analysis of the energy dependence for several CR modulation items was also performed by other researchers in the past, although the question of the data reliability has been often raised. For example, by using Climax, Huancayo, Moscow, Kiel and Calgary, the authors of [23] were forced to

use 12-point moving averages of monthly data in wavelet analysis; as a consequence, the time precision got lost.

The necessity to use long data series from several NMs with different cut-off rigidities was also underlined by [24], after a work performed to estimate CR periodicities during solar cycle 23, where only Oulu NM data were employed.

Also [25] investigated in detail the time behaviour of CR intensity registered at Oulu for the period 1965-2011. Interesting results were obtained but the rigidity dependence of them could not be established, because only a single measurement point was used.

Finally, the valuable work of the “modulation potential reconstruction”, extended back till July 1936 [26], demonstrated a better reliability for the obtained results when data from several NMs are used (Goose Bay, Oulu, Kerguelen, Kiel, Hermanus, Rome, Climax, Mt. Washington).

This reinforces the relevance of good long-term series of CR data from different terrestrial locations.

In conclusion we remind that CR detectors are not only an outstanding heritage (as it is often believed), but also the potential sources of data for novel research.

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