# LONG-TERM COSMIC RAY INTENSITY VS. SOLAR PROXIES: A SIMPLE LINEAR RELATION DOES NOT WORK

**K. Mursula**[1], **I. G. Usoskin**[2], **and G. A. Kovaltsov**[3]

[1]*Department of Physical Sciences, POB 3000, FIN-90014 University of Oulu, Finland*
[2]*Sodankylä Geophysical Observatory, POB 3000, FIN-90014 University of Oulu, Finland*
[3]*Ioffe Physical-Technical Institute, RU-194021 St.Petersburg, Russia*
E-mail: Kalevi.Mursula@oulu.fi; Ilya.Usoskin@oulu.fi; koval@TD4131.spb.edu

## ABSTRACT

It was recently suggested by Lockwood et al. (2000, 2001) that the cosmic ray intensity in the neutron monitor energy range is linearly related to the coronal source flux, and can be reconstructed for 140 years using the estimated long term coronal flux. Moreover, by reversing this relation, they reconstructed the coronal flux on the 500-year scale using the cosmogenic $^{10}Be$ data as an index of cosmic ray intensity. Here we show that a linear regression is oversimplified and leads to unphysical results on long time scales. In particular, the reconstructed cosmic ray intensity has a steep trend which is four times larger than the allowed upper bound. The reconstructed cosmic ray intensity exceeds the local interstellar cosmic ray flux around 1900. We argue that the unphysical results using a linear assumption are due to the oversimplified approach which does not account for complexity and significant nonlinearity of cosmic ray modulation in the heliosphere. We show also methodologically that there is no homogeneous linear relation between coronal source flux and cosmic rays.

## 1. INTRODUCTION

Recently, (Lockwood et al. 1999, 2000) and (Lockwood 2001) (denoted as L01 throughout this paper) estimated the coronal source flux $F_s$ for the time after 1868 using the geomagnetic *aa* index. L01 also suggested that $F_s$ is linearly related to the intensity of cosmic rays (CR) and calculated the correlation between $F_s$ and the CR as measured by the Climax neutron monitor (NM) and by the concentration of $^{10}Be$ isotope in Greenland ice. (The geomagnetic cutoff rigidity of Climax NM is about 3 GV). The logical chain of the linear relations used in L01 is as follows:

$$F_s \iff CR(NM) \quad (1953-1999) \quad (A)$$
$$F_s \implies CR(NM) \quad (1868-1999) \quad (B)$$

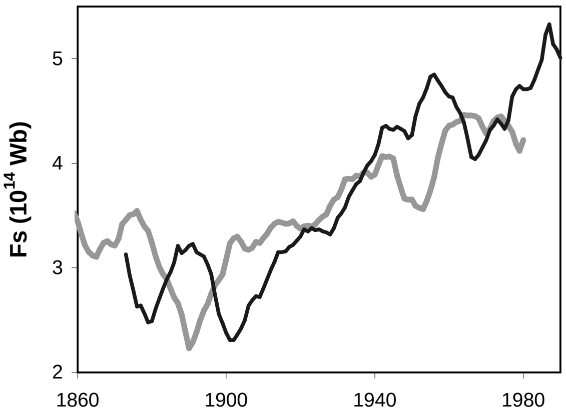

*Figure 1. The coronal source flux $F_s$ constructed by the method of Lockwood et al. (2000) from the geomagnetic aa series (black curve) and from the cosmogenic $^{10}Be$ isotope (grey curve). The curves are 11-year running mean values.*

$$^{10}Be \iff F_s \quad (1868-1985) \quad (C)$$
$$^{10}Be \implies F_s \quad (1423-1985) \quad (D)$$

First, the linear relation between $F_s$ and the cosmic ray (CR) intensity for the neutron monitor era was calculated (statement A) and then this relation was used to reconstruct the NM cosmic ray intensity for the much longer period of 1868-1996 (statement B). Next, they calculated the linear relation between $F_s$ and the cosmic ray intensity as presented by the $^{10}Be$ isotope (Beer 2000) for the period 1868-1985 (statement C), and used this relation and the long record of $^{10}Be$ data in order to reconstruct the very long-term profile of $F_s$ since 1423 (statement D). This reconstructed $F_s$ is suggested by L01 as a new index of solar activity for early times. It is important to note that only linear relations were used in all steps by L01.

We note that the entire coronal source flux concept and its relation to the solar global magnetic field is

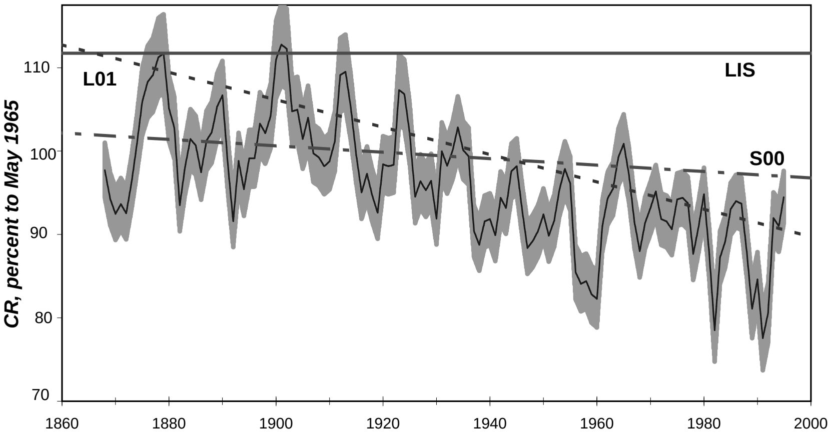

*Figure 2. Climax NM count rates (in percent to May 1965) reconstructed from the $F_s$ series (black curve) with grey shading denoting the $1\sigma$ error. The constant LIS line corresponds to the local interstellar CR spectrum, dotted L01 line depicts the trend in CR according to L01, and the dash-dotted S00 line represents the largest possible negative CR trend (Stozhkov et al. 2000).*

heavily criticized (Kotov & Kotova 2001; Li et al. 2001; Richardson & Cane 2001; Hildner et al. 2001; Zhao et al. 2001). Not discussing this issue, in this paper we show that a linear relation between $F_s$ and CR adopted in L01 is oversimplified and leads to unphysical results. We restrict our study to the last 140 years (statements A-C) since several data series exist for this time period. We calculated the coronal source flux $F_s$ since 1868 from the *aa* index using the recipe published by Lockwood et al. (1999). (The geomagnetic recurrency index (Sargent 1985) employed in $F_s$ was calculated directly from the *aa* series.) The source flux $F_s$ depicted in Fig. 1) is in an excellent agreement with the corresponding $F_s$ series in L01. In the subsequent sections we will reproduce and discuss the relations A to C and show how they result to unphysical results.

## 2. COSMIC RAY RECONSTRUCTION

Following the analysis by L01, we found the following linear regression between annual values for the Climax NM data and the calculated source flux $F_s$

$$CR(NM) \ = (5.25 \pm 0.11) - (0.28 \pm 0.025) \cdot F_s \quad (1)$$

where CR(NM) is given in counts/h/$10^5$ and $F_s$ in $10^{14}$ $Wb$. This coincides with the regression suggested by L01. Using this linear regression for the period of 1953-1999, we have reconstructed the CR(NM) for the time since 1868, similarly to L01. The reconstructed CR(NM) series is shown in Fig. 2) together with the $1\sigma$ error. This series is in a good agreement with the results presented by L01 (see, e.g., Fig. 10 there). Since the NM count rates were highest in May 1965 during the last five solar cycles, it is common to normalize NM count rate per 100% in May 1965.

In L01 they estimated that "...the average fluxes of CR above 3 GeV were approximately 15% higher in 1900 than they are now". Let us now analyse this reconstructed long-term CR intensity in more detail. Note that CR intensity during the solar minimum periods corresponds to the residual modulation in a quite heliosphere. E.g., Stozhkov et al. (2000) calculated the trend in the residual modulation to estimate the stability of CR intensity outside the heliosphere. They found that this trend for the Climax NM data since 1953 is $-0.04 \pm 0.04$ % /year (dash-dotted S00 line in Fig. 2). The data of CR recorded by ion chambers since 1937 imply that this trend (if any) was not higher earlier and can serve as an upper bound (Ahluwalia 2000; Stozhkov et al. 2001). The similarly calculated trend for the reconstructed CR(NM) series is much steeper $-0.16 \pm 0.07$ % /year (dotted L01 line in Fig. 2) which is in disagreement with the above results.

There is an absolute upper bound for CR(NM) which is related to the local interstellar spectrum (LIS) of cosmic rays outside the heliosphere. We have depicted this upper bound in Fig. 2, calculated using the method by Usoskin et al. (2001a) with LIS as given by Burger et al. (2000) and the Climax NM specific yield function (Debrunner et al. 1982; Nagashima et al. 1989). Accordingly, this is the absolute upper bound to CR(NM) intensity, and corresponds to the case of no heliospheric suppression. However, the reconstructed CR intensity reaches this upper bound several times due to the overshooting trend at around 1900 due to extrapolation of the linear regression (Eq. 1) far beyond the range where it was calculated. Although it is discussed that CR level might exceed LIS during extremely quite periods, e.g., Maunder minimum, due to a residual modulation beyond the heliospheric termination shock (McDonald et al. 2000; McCracken & McDonald 2001), the CR intensity was estimated to be well below LIS around 1900, using data of various indirect proxies (O'Brien et al. 1991; Bonino et al. 2001; McCracken & McDonald 2001; Scherer et al. 2001). Therefore, following (Usoskin et al. 2001a), we can estimate the momentary modulation efficiency as

$$M(t) \; = \; \frac{CR_{LIS} - CR(t)}{CR_{LIS}} \qquad (2)$$

Fig. 3 shows the scatter plot of this modulation efficiency vs. the coronal source flux $F_s$, using Climax NM data since 1953. The best fit linear regression (Eq. 1) is also depicted. On one hand, this linear regression fits well the scatter plot allowing Lockwood (2001) to extrapolate it to the area of low $F_s$, and correspondingly to $M < 0$. On the other hand, one can not expect a linear relation between the magnetic field, affecting the diffusion coefficient, and CR intensity. In a simple diffusion case, the relation would be exponential but in the real modulation it is much more complicated and significantly non-linear. In order to illustrate this, we separate the scatter plot in three regions of $F_s$. One can see (solid lines in Fig. 3) that the regression (Eq. 1) is not homogeneous, as expected from theoretical views. Only in the range of moderate $F_s$ (4–5.5·$10^{14}$Wb), the relation is more or less linear leading for the entire Eq. 1. For high values of $F_s$, above $5.5 \cdot 10^{14}$Wb, the correlation nearly disappears as the CR modulation is affected mostly by global merged interaction regions rather than the overall magnetic field (e.g., Potgieter et al. (1998) and references therein). In the range of lower values of $F_s$, below $4 \cdot 10^{14}$Wb, the modulation effect of $F_s$ becomes much smaller as seen by only slightly inclined line in Fig. 3. From physical point of view, one should expect that $M \rightarrow 0$ at $F_s \rightarrow 0$ which is not true in the linear case (line "L" in Fig. 3). As an example of a corresponding function, a power law fit is shown in the Figure (line "PL"). Giving even better formal fitting to the existing points than the linear regression, the power law regression would yield the maximum value of the reconstructed CR intensity around 1900 being about 8% higher than in 1965 (cf. 15% suggested by L01). We do not suggest a power law regression to reconstruct CR intensity in the past but rather illustrate that large uncertainties, which almost deny any conclusion, arise when a regression is extrapolated far beyond the established range without caveats and physical reasoning.

## 3. $F_S$ VS. COSMOGENIC ISOTOPES

Although direct CR measurements are not available to verify the relation $F_s$ vs. CR in the range of small values of $F_s$, data of cosmogenic isotopes are used a proxy for long-term variations of CR intensity in the past (Beer 2000). Following the recipe by L01, we have found the following linear relation between 11-year running mean values of $^{10}Be$ and $F_s$ (statement C) for the time interval 1873-1980:

$$F_s \; = \; b - \; m \cdot C_{Be} \qquad (3)$$

where $F_s$ is given in $10^{14}$ $Wb$ and $C_{Be}$ in $10^4$ $atom/g$ and $m = 3.1 \pm 0.4$ and $b = 6.3 \pm 0.3$. Using this relation we have reconstructed $F_s$ for 1873-1980 and depicted it in Fig. 1. This is in a good agreement with the results presented in L01 (see, e.g., the latter part of Fig. 14 there).

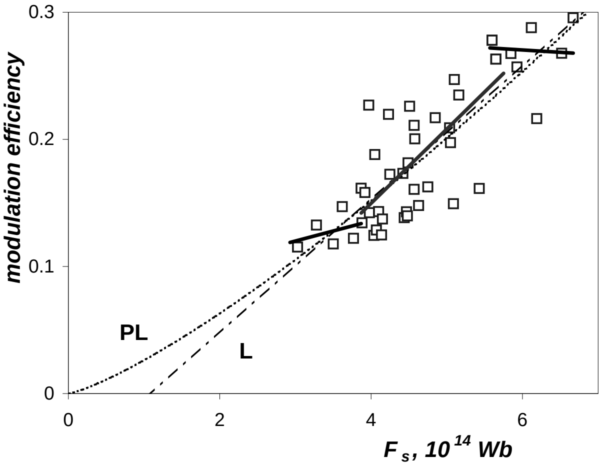

*Figure 3. Scatter plot of yearly modulation efficiency vs. coronal source flux $F_s$. Solid lines depict linear regression for three regions of $F_s$ values ($< 4$, $4 \div 5.5$, and $> 5.5 \cdot 10^{14}$ Wb). Dash-dotted and dotted lines (labeled as "L" and "PL") depict the best fit linear (Eq. 1) and power law regression, respectively.*

One can see in Fig. 1 that, despite some similarity in the increasing trend, the source flux reconstructed from $C_{Be}$ (grey curve) is in a disagreement with the "original" flux derived from the $aa$ index (black curve). It is interesting to note that, during the depicted interval 1873-1980, the relation between $F_s$ and $C_{Be}$ was strongly inhomogeneous. Fig. 4 shows the scatterplot separately for three periods. During periods (1873–1903 and 1944–1980) when $F_s$ was roughly stable (see Fig. 1), the correlation between $F_s$ and $C_{Be}$ was slightly positive (the slope of regression in Eq. 3 was $m = -1.6 \pm 0.3$ and $m = -0.5 \pm 0.4$, respectively). This is also seen in Fig. 1 as a rough antiphase between the $F_s$ reconstructed from $^{10}Be$ and the "original" flux. The two stable periods were intervened by a period of a monotonous increase of $F_s$ in 1903–1944. The correlation for that period was strongly negative, with $m = 5.5 \pm 0.3$. Accordingly, the relation between $F_s$ and $C_{Be}$ is completely different for stable periods and for periods of fast monotonous changes. Thus, there is no simple linear relation between $F_s$ and CR intensity, and therefore the procedure of reconstructing $F_s$ from $^{10}Be$ in L01 is invalid.

## 4. CONCLUDING REMARKS

In this paper we have shown that the linear relation between cosmic ray intensity and the solar coronal magnetic flux $F_s$ adopted by Lockwood et al. (2000); Lockwood (2001) is not valid in the long-term time scale leading to unphysical results. This result can be understood from two points of view.

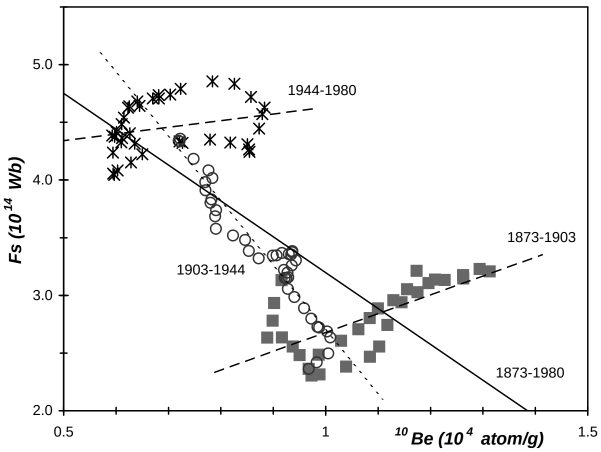

*Figure 4. Scatterplot of 11-year smoothed values of $F_s$ vs. $^{10}$Be concentration for 1873-1980. Solid line represents the best linear regression for the entire period while grey squares and dashed line, open circles and dotted line, and asterisks and dashed line depict points and the best linear regression for 1873-1903, 1903-1944 and 1944-1980, respectively.*

From a physical point of view, a simple linear influence of the coronal source flux (intensity of the interplanetary magnetic field, IMF) on the cosmic ray intensity is oversimplified. While IMF is important for heliospheric CR modulation (Cane et al. 1999; Belov 2000), transport of cosmic rays in the heliosphere is influenced also by other, not less significant, agents like the heliospheric neutral sheet, solar wind speed, IMF polarity, etc. (see, e.g., Belov (2000) and references therein). Moreover, CR intensity in the Earth vicinity must have an upper bound corresponding to LIS, which is not adopted in the frame of the linear approach.

Methodologically, extrapolating a linear regression far beyond the range where it has been established is not straightforward. In particular, the heliospheric modulation of CR is very complicated and significantly non-linear, and the relation may be approximated by a linear regression only within a very limited time interval (Fig. 3). E.g., the relation between $F_s$ and CR was established only during 45 years when $F_s$ was fairly stable and high (Fig. 4) and then extended for 130 years, including periods of rapid changes of $F_s$ and of stable but low $F_s$ values.

Concluding, the use of a linear regression between two not directly related parameters (e.g., coronal source flux and cosmic ray intensity as used by Lockwood (2001)) to long-term reconstruction leads to huge uncertainties which virtually void any conclusion drawn on such an extrapolation.

**Acknowledgements.** We thank the Academy of Finland for financial support. IGU acknowledges INTAS grant YSF 00-82.

## REFERENCES

Ahluwalia, H. S., Geophys. Res. Lett., 27, 1603, 2000.

Beer, J., Space Sci. Rev., 93, 107, 2000.

Belov, A.V., Space Sci. Rev., 93, 79, 2000.

Bonino, G. et al., in Proc. 27th Internat. Cosmic Ray Conf., Hamburg, 9, 3769, 2001.

Burger, R.A. et al., J. Geophys. Res., 105, 27447, 2000.

Cane, H.V., G. Wibberenz, I.G. Richardson, T.T. von Rosenvinge, Geophys. Res. Lett., 26, 565, 1999.

Clem, J.M., L.I. Dorman, Space Sci. Rev., 93, 335, 2000.

Debrunner H., E.Flueckiger, J.A.Lockwood, 8th Europ. Cosmic Ray Symp., Rome, 1982.

Hildner, E. et al., AGU Spring Meeting 2001, abstract #SH51A-08.

Kotov, V.A., and I.V. Kotova, Astron. Lett., 27, 260, 2001.

Li, Y. et al., AGU Spring Meeting 2001, abstract #SH52A-02.

Lockwood, M., J. Geophys. Res., 106(A8), 16021, 2001

Lockwood M., R. Stamper, M.N. Wild, Nature, 399, 437, 1999.

Lockwood, M., S. Foster, in: "The Solar Cycle and Terrestrial Climate", eds. A. Wilson, ESA Publications SP-463, 85, 2000.

McCracken, K. G. and F. B. McDonald, in Proc. 27th Internat. Cosmic Ray Conf., Hamburg, 9, 3753, 2001.

McDonald, F. B. et al., J. Geophys. Res., 105(A1), 1 2000.

Nagashima K. et al., Nuovo Cimento, 12(C2), 173, 1989.

O'Brien, K., A. et al., in: C.P. Sonnet, M.S. Giampapa, M.S. Matthews (eds.), The Sun in time, the University of Arizona, Tucson, 1991, p.317.

Potgieter, M. S., Space Sci. Rev., 83, 147, 1998.

Richardson, I.G., and H.V. Cane, AGU Spring Meeting 2001, abstract #SH51A-11.

Sargent, H.H., III, J. Geophys. Res., 90, 1425, 1985.

Scherer, K. et al., in Proc. 27th Internat. Cosmic Ray Conf., Hamburg, 10, 4031, 2001.

Stozhkov, Y.I., P.E. Pokrevsky, V.P. Okhlopkov, J. Geophys. Res., 105, 9, 2000.

Stozhkov, Y.I., et al., in Proc. 27th Internat. Cosmic Ray Conf., Hamburg, 9, 3883, 2001.

Usoskin, I.G., et al., J. Geophys. Res., 103(A5), p.9567, 1998.

Usoskin, I.G. et al., Adv. Space Res., 27, 565, 2001a.

Usoskin, I. G., et al., in Proc. 27th Internat. Cosmic Ray Conf., Hamburg, 9, 3810, 2001b.

Zhao, X. et al., AGU Spring Meeting 2001, abstract #SH52A-01.