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Study of Time Lags and Hysteresis between Solar Indices and Cosmic Rays: Implications for Drifts and Modulation Theories

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A detailed analysis of the hysteresis effects between solar activity indices (sunspot number, 10.7 cm. solar flux, solar flare index), and cosmic ray intensity has been done. Neutron monitor and solar data extending to last 50 years period, covering five solar activity cycles (19-23), and as many alternating solar polarity states (two $A > 0$, and three $A < 0$) have been analyzed. Hysteresis plots between individual solar indices and cosmic ray intensity show significant solar activity cycle dependent and solar magnetic cycle dependent differences. Area of the hysteresis loops, time lag between solar index and cosmic ray intensity, and the rate of cosmic ray intensity decrease with solar index during even and odd numbered cycles have been calculated and noticeable differences have been found. Implications and consequences of observed differences have been discussed. Differences between time lags and intensity decrease rate during opposite polarity states of the solar magnetic field and the heliosphere ($A > 0$ and $A < 0$) have also been observed. These differences appear to be related to polarity states of the heliosphere and particle drifts in the heliosphere.

1. Introduction

The ~11-year solar cycle variation in cosmic ray intensity observed at earth is anti-correlated with solar activity with some time lag. Forbush [1] first demonstrated that cosmic ray variations lagged behind sunspot activity by 6 to 12 months. The observed lag was later attributed [2] as due to dynamics of the build up and subsequent delayed relaxation of the modulating region. In many subsequent studies (e.g. [3-5]) the observed time lag was used to infer about the size of the modulating region (the heliosphere). However, Hatton [6] questioned the use of time lag as a parameter to estimate the modulation boundary.

Hysteresis effect between long-term variation in cosmic ray intensity and solar activity has been studied since long (e.g. [7]). However, some of the recent studies of time lag and hysteresis effect (e.g. [8-16]) have led to renewed interest in the interpretation, implication and consequences of observed differences between time lags in odd and even cycles as well as differences in the shape, size etc. of hysteresis loops during odd and even cycles. In this paper we have studied the time lag and hysteresis effect between long-term variation in cosmic ray intensity and solar activity during the period 1952-2003, covering solar cycles 19, 20, 21, 22 and 23.

2. Discussion

In most of earlier studies of hysteresis effect, yearly mean of cosmic ray intensity and a solar activity index (e.g. sunspot number) have been used. These plots show differences in features during different solar cycles. In order to decide about a more suitable period over which, if averaged, the data may provide better insight of hysteresis phenomenon we determined the average time lag, using data for the period 1954-2003, between the 10.7 cm. solar flux and cosmic ray intensity. To determine it, we have calculated the correlation coefficient between solar parameters and cosmic ray intensity with time lag from 0 to 29 months and determined the time lag corresponding to optimum correlation. It is found to be six months. Then, we plotted the hysteresis curve for solar cycles 19, 20, 21, 22 and 23 by taking six-monthly mean of cosmic ray and solar data. We have calculated the area of the each hysteresis loop, and the rate of change of cosmic ray intensity with solar activity (see also [11]).

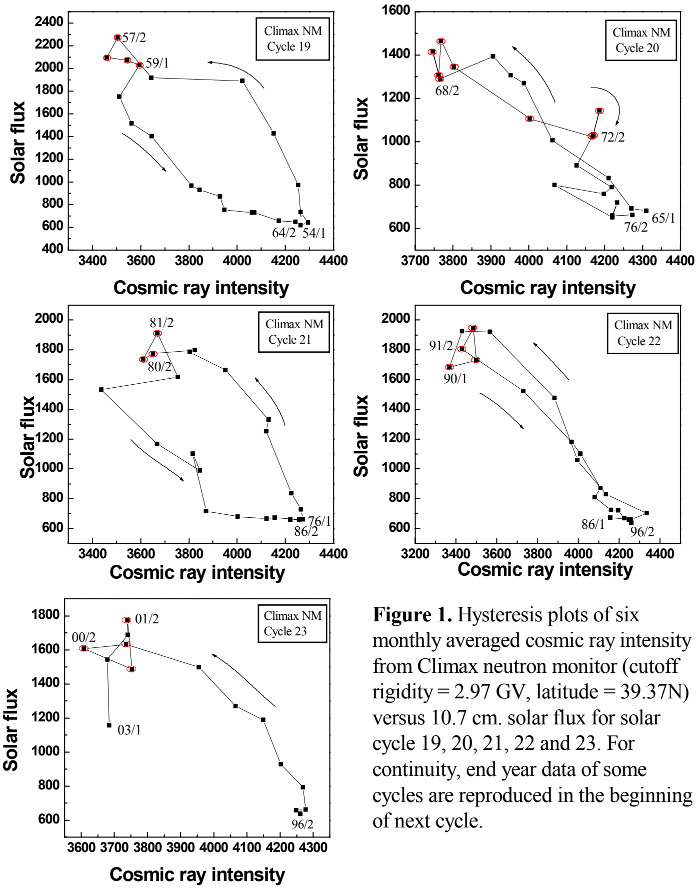

Figure 1. Hysteresis plots of six monthly averaged cosmic ray intensity from Climax neutron monitor (cutoff rigidity = 2.97 GV, latitude = 39.37N) versus 10.7 cm. solar flux for solar cycle 19, 20, 21, 22 and 23. For continuity, end year data of some cycles are reproduced in the beginning of next cycle.

The difference in phase lag, loop area, and rate of change in CR intensity with solar parameters during odd and even cycles is evident. Hysteresis plots of cosmic ray intensity with sunspot numbers (cycle 19–23)/and solar flare index (cycle 21-23) show similar patterns in respective solar cycles. Another worth mentioning feature of 6-monthly averaged hysteresis loops is that small secondary loops (cyclic changes) of intensity are superimposed at/near solar maximum when solar polarity reversal takes place.

We have determined the time lag for positive (A > 0) and negative (A < 0) epochs (excluding the periods of polarity reversal), 1952-56 (A > 0), 1961-68 (A < 0), 1973-79 (A > 0), 1982-89 (A < 0) and 1992-99 (A > 0). It is found that time lag is 9-10 months during A < 0 epoch when the polarity of the heliosphere above current sheet is negative (see Table 2). The time lag between cosmic ray intensity and solar activity is much smaller (3-5 months) in opposite polarity condition of the heliosphere (A > 0). It is interesting to note that in both the cases, whether based on solar activity cycles or solar polarity epochs, time lag is longer when the recovery takes place in A < 0 polarity condition as compared to A > 0 polarity condition.

Table 1. Time lag between 10.7 cm. solar flux and cosmic ray intensity, with maximum values of correlation coefficient (R) for solar cycles 19, 20, 21, 22 and 23.

Solar cycle	19	20	21	22	23
Lag (months)	10	01	11	03	14
R	-0.932	-0.855	-0.893	-0.925	-0.915

Table 2. Time lag between 10.7 cm. solar flux and cosmic ray intensity with maximum value of correlation coefficient (R) during different polarity epochs.

Solar polarity	1952-56 (A > 0)	1961-68 (A < 0)	1973-79 (A > 0)	1982-89 (A < 0)	1992-99 (A > 0)
Lag (months)	04	10	03	09	05
R	-0.836	-0.868	-0.829	-0.857	-0.902

In order to determine the size of the hysteresis loops, we have determined the area of each cycle. These values are given in Table 3. It is clear from this table that areas of odd cycle loops are much larger than even cycle loops as observed earlier e.g. [11]. Otaola et al. [17] suggested that the difference in behaviors of cosmic ray intensity during odd and even solar cycles are due to parallel and anti-parallel states of the polarity of the polar magnetic field of the sun relative to galactic magnetic field. This interpretation is based on a hypothesis [8] that when polar magnetic field of the sun is nearly parallel to the galactic magnetic field, they can easily connect, so that galactic cosmic rays, especially those of low rigidities, could enter more easily into the heliosphere along the field lines of force, as compared to anti parallel states of the magnetic fields.

Table 3. Area of modulation loops (x 10^5)

Solar Cycle	19	20	21	22	Av. odd cycle	Av. even cycle
Area	589.724	26.571	447.918	122.279	518.821	74.425

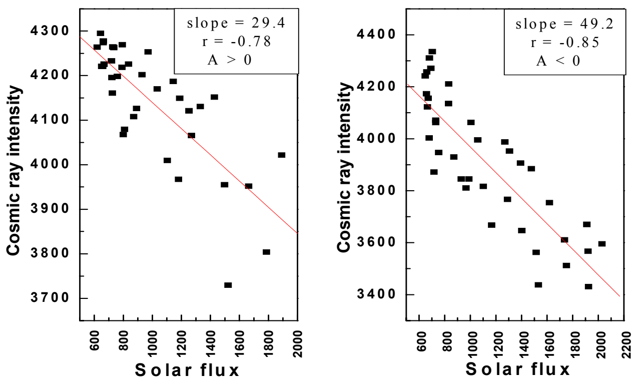

Figure 2. Scatter plots of solar index with cosmic ray intensity along with the best-fit curve.

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Figure 2 shows the scatter plots of six monthly solar index with cosmic ray intensity, along with the best fit curve, in different polarity epochs. It is seen that, in general, cosmic ray response to solar index is more during A < 0 than A > 0 as evident from the value of slope written at the top of the diagram. Different processes (convection, diffusion, adiabatic deceleration and drifts) influence cosmic ray transport in the heliosphere. Suggestions have been put forward that during even cycles, convection plays the most important role, while diffusion dominates during odd cycles [8]. However, for a better understanding of odd-even cycle difference, the influence of gradient in, and curvature of interplanetary magnetic field on the transport of cosmic ray should also be considered [11, 13, 16].

3. Conclusions

The hysteresis loops obtained for different cycles show differences between even and odd cycles. Areas of odd cycle loops are much larger than even cycle loops. The time lag between cosmic ray intensity and the solar index is different in odd (10-14 months) and even (1-4 months) cycles. Differences in time lag between periods of $A < 0$ polarity (9-10 months) and $A > 0$ polarity (3-5 months) have also been found. Lag is more when the recovery phase of long-term (~ 11-years) modulation lies in $A<0$ epoch. The difference in time lag between odd and even cycles, and between $A < 0$ and $A > 0$ epoch, may not related to level of solar activity but to motion of cosmic ray particles in the large scale heliospheric magnetic field influenced by polarity state of the heliosphere. Small cyclic changes are superposed around solar maximum (and polarity reversal) period of almost every cycle (odd and even). This additional feature may be due to Gnevyshev gap effect – double peak structure in the maximum phase of solar activity cycles – or due to peculiar particle drift effect at solar maximum. At solar maximum (when the tilt of the current sheet is close to 90^0) the particles see the fields, in the polar regions, of both positive and negative polarity and they drift sometimes inward and sometimes outwards [18]. The rate of decrease in intensity of cosmic rays with solar activity is greater during $A < 0$ than $A > 0$; this difference appears to be related to drift effects in the heliosphere.

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