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Evidence of charge drift effect in solar modulation of Galactic Cosmic Rays

G. Boella[1,2], **M. Gervasi**[1,2], **S. Mariani**[1], **P.G. Rancoita**[1], **and I. Usoskin**[1,3]
[1]*INFN-Milano, Milano, Italy*
[2]*and Physics Department, University of Milano-Bicocca, Milano, Italy*
[3]*and Ioffe Physical Technical Institute, St. Petersburg, Russia*

Abstract

Drift effect can play an important role in the modulation of galactic cosmic rays. Cosmic rays of opposite charge undergo different transport in the Heliosphere, depending on the solar activity level. In the present paper a systematic investigation of the charge drift effect and its dependence on the solar activity phase is presented. The method is based on a correlation study among experimental data of cosmic ray fluxes of low (below 300 $MeV_{/amu}$) and higher energy (above several GeV) within the period 1973 - 1995 (two solar cycles). It is shown that the change of the proton flux might be as large as 40%, for energy of several hundred MeV, due to the drift effects, within a solar cycle.

1 Introduction

The long scale structure of the heliospheric magnetic field is characterized by inhomogeneities generating drift motion of low energy galactic cosmic rays (GCR), as observed for electrons and positrons (Clem et al., 1996). This is one of the long term leading mechanisms in solar modulation of GCR. During periods whith positive magnetic field polarity ($A > 0$) positive charged particle (like protons and positrons) have higher probability to reach the Earth from polar regions of the heliosphere, while negative charged particles (like electrons and antiprotons) come mainly from equatorial regions. The situation is inverted during solar cycles with $A < 0$. The propagation through polar or equatorial regions means a different modulation is suffered by low energy protons even under substantially similar modulation conditions. In fact the measured spectrum of protons during a $A > 0$ solar minimum is considerably higher than what is found during $A < 0$ cycles, expecially below $1\,GV$ (Garcia-Munoz et al., 1986).
The tilt angle α of the Heliospheric Current Sheet (HCS) also influences the spectrum of the GCRs measured at the Earth. In particular during $A < 0$ periods for positive charged particles (and during $A > 0$ periods for negative charged ones) the more α increases the more drift effects contribute to the suppression of the GCR flux at the Earth.
In a series of papers (Kota and Jokipii, 1983; Reinecke et al., 1997) it is shown that drift effects play an important role in modulation, in particular during periods of solar minimum. Even better results have been obtained developing time dependent models of solar modulation (LeRoux and Potgieter, 1995), but the actual influence of the drift mechanism have not been established yet.
We have developed a measure–based method to estimate drift efficiency for galactic cosmic rays of several energies ($0.4 - 1.5\,GV$) for different solar activity levels.

2 Data description and analysis

We used data collected by IMP-8 satellite and Climax Neutron Monitor and shown in figure 1. IMP-8 (Sarris et al., 1989 and references therein) has been lounched in 1973 to realize a continuous monitoring of heliospheric conditions mainly measuring cosmic rays. MED, one of the istruments onboard the satellite, has been detecting mainly protons and helium ions. MED data have been provided in 7 channels, 2 for protons ($P1$, $29-63$ $MeV_{/amu}$; $P2$, $121-230$ $MeV_{/amu}$) and 5 for alpha particles ($A1$, $29-63$ $MeV_{/amu}$; $A2$, $81-101$ $MeV_{/amu}$; $A3$, $134-168$ $MeV_{/amu}$; $A4$, $168-198$ $MeV_{/amu}$; $A5$, $168-381$ $MeV_{/amu}$).

The Climax NM, set in Colorado at an altitude of 3600 mt, is mainly sensitive to secondary neutrons produced by primary protons and helium interacting in the atmosphere. The geomagnetic cutoff of the station is about 3 GV. Data cover the period from 30 October 1973 to 14 April 1995. The Climax NM counting rate (in this paper the value, expressed in counts/sec, is rescaled by 200) is founded to be dependent on the proton primary component for 75 % and on the helium one for 20 %. While IMP-8 counting rate is believed to be dominated by drift effects, NM's one is independent of drift. In fact only GCR with kinetic energy below 4 $GeV_{/amu}$ (Bieber & Matthaeus, 1997) are interested by the drift mechanism and we have estimated an upper limit of 1 % to the change of the Climax NM counting rate due to drift effects. We have compared fluxes of low energy GCR collected during periods belonging to consecutive solar cycles and set together by the same recorded NM counting rate. Any difference found comparing these fluxes should be attributed to drift mechanism. We have compared separately rising and declining phases of the solar activity level; an example is shown in figure 2, where declining phases data have been represented. Strong solar events and periods of deep forbush decrease have been excluded from our long term approach. We have defined the parameter R to estimate the drift effect. R is the ratio among IMP-8 fluxes measured in solar cycles with opposite polarity for the same value of NM counting rate. No drift effects means $J^{+}(NM) = J^{-}(NM)$ for GCR fluxes. The more $R \neq 1$ the larger the drift effect is. This parameter depends both on rigidity and NM average counting rate.

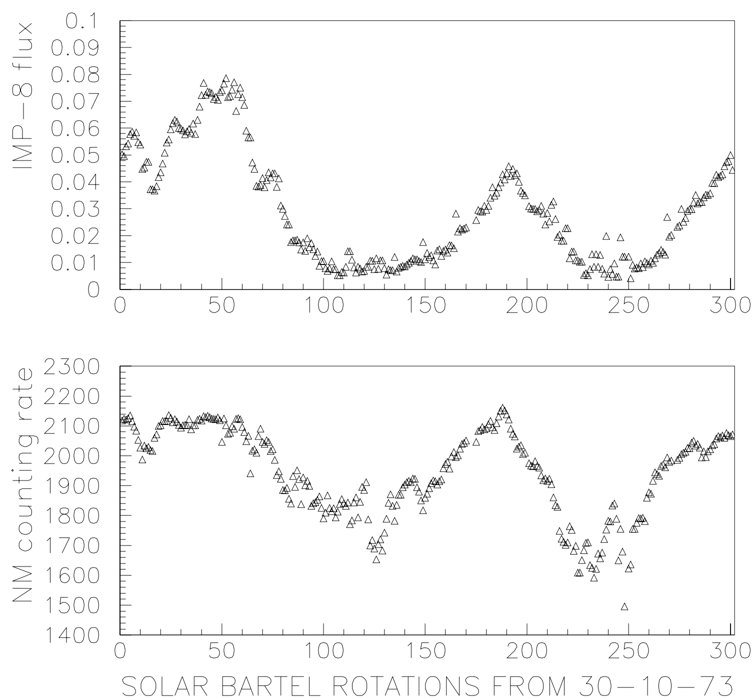

Figure 1: Measurements of IMP-8, P1 channel (upper panel) and of Climax NM (lower panel), 1973-1997. IMP flux is given in $counts/(cm^2 \;\; s \;\; sr \;\; GeV_{/amu})$; NM counting rate is given in $counts/s/200$.

$$R(NM)_E = \frac{J^{-}(NM)_E}{J^{+}(NM)_E} \tag{1}$$

Original data are averaged on 26 days. They show significant statistical errors as well as a high dispersion due to short term changes in modulation. We binned data in 6 groups with respect to the NM counting rate. The number of points per bin has been changed in order to be *high* enough to reduce statistical fluctuation but *low* enough to avoid large systematic effects inside a single bin. Moreover, corresponding intervals should be similar in $A > 0$ and $A < 0$ periods for each energy channel in order to compute the ratio R.

We considered two sources of error: the intrinsic fluctuation of the data inside a single bin and the instability of the average with respect to different choices of the bins.

3 Discussion

The values of R for the lowest energy channels with high NM rates are clearly below 1. The effect of drift is reduced with rising solar activity and rising energy, as it is qualitatively forseen by drift models too (i.e. Potgieter et al., 1993).

Plotting R as a function of NM, shown in figure 3, for the lowest energy channel the drift effect is clearly evident above a threshold value of NM. On the other hand no effect is shown in the highest energy channel. Simmetrically a plot of R as a function of energy, as in figure 4, shows a consistent drift effect with low solar activity. The effect is larger at low energy and is reducing with rising energy. No effect is found for any energy with high solar activity.

Declining and rising phases in solar activity have shown some difference. In the declining phases the effect seems to be deeper than in rising one. Probably while the solar activity is declining and going toward a solar minimum, the heliosphere reaches a situation of high drift efficiency, caused by the progressive disappearing of disturbative barrier phenomena, as GMIRs (Reinecke et al. 1997).

We observed that the parameter which better couple protons and alpha particles is different from declining to rising phases: respectively kinetic energy per nucleon and rigidity times the β factor.

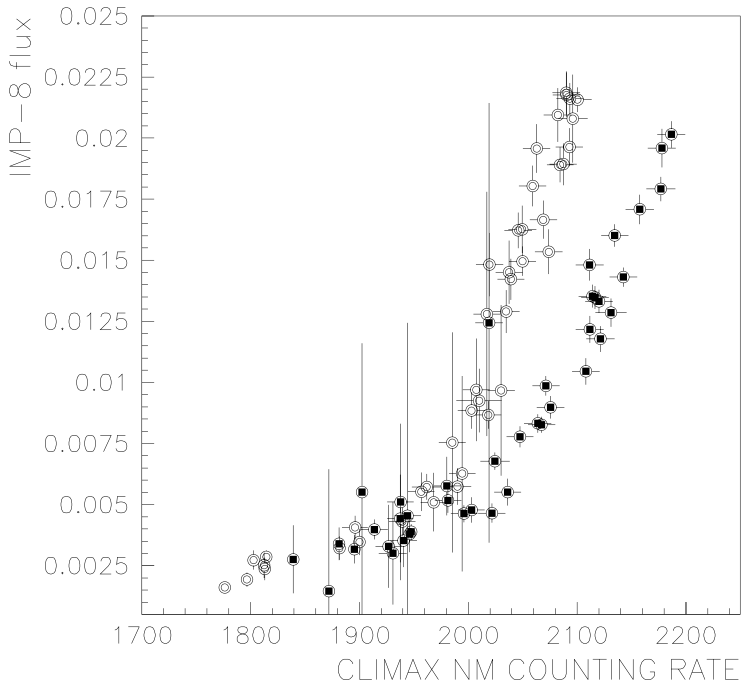

Figure 2: IMP-8 A1 channel flux vs NM counting rate (for units see figure 1). We compare data taken during the same (descending) phase of two consecutive solar cycles. Open circles are data of cycle 22 and solid circles of cycle 21.

4 Conclusion

As it is shown in the table, during periods of solar minimum drift is responsible for up to 40 % differences in fluxes at kinetic energy of 50 MeV for consecutive solar cycles. Above 300 MeV the effect is below 10 %. In the table we quoted the parameter $1 - R \simeq |J^{+} - J^{-}|$ at the solar minimum. Our results for periods of solar minimum confirm the models predictions (Reinecke et al., 1997).

We have extended the analysis out of the solar minimum, where drift effects become weaker with rising solar activity and there are not reliable models. It is also possible to use these results to estimate the drift effects in the modulation of the antiproton to proton ratio. In fact reversing the polarity when the proton flux is decreasing the antiproton one increases, producing an even larger variation. For instance we estimate a variation of the antiproton to proton ratio of 60 $\pm$ 20 % at at the solar minimum for kinetic energy of 100 $MeV_{/amu}$.

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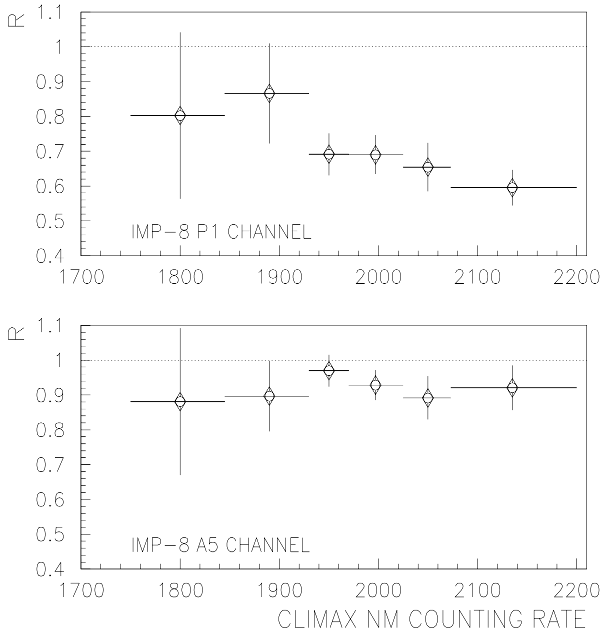

Fig. 3

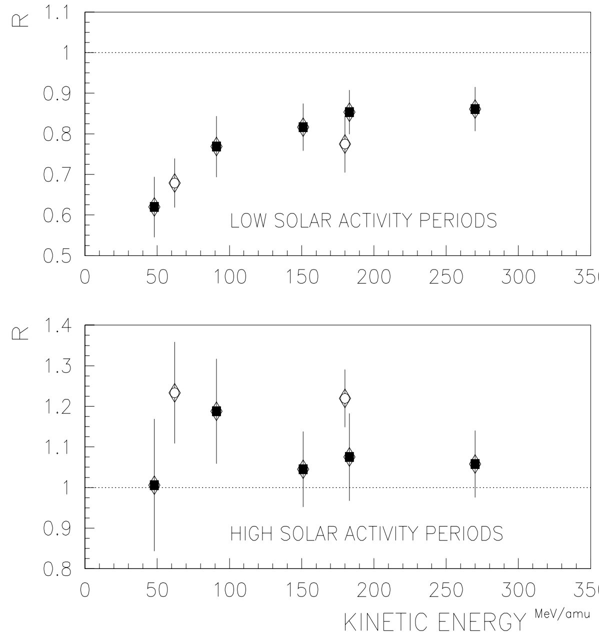

Fig. 4

Figure 3. The drift parameter R as a function of the NM counting rate, for protons with $E = 29 - 63$ $MeV_{/amu}$ (upper panel) and for alpha with $E = 168 - 381$ $MeV_{/amu}$ (lower panel).
Figure 4. R vs kinetic energy for periods with low ($\sim$ 2150 counts) and high ($\sim$ 1850 counts) solar activity. Open symbols for protons, solid symbols for alpha particles.

p [MeV/c]	E [$MeV_{/amu}$]	$1 - R$ [%]
310	50	40 ± 10
450	100	25 ± 8
650	200	20 ± 7
870	300	14 ± 6

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