# Muon and Neutron Observations in Connection with the Corotating Interaction Region

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## Abstract

Ground cosmic ray observations are used for studying several kinds of interplanetary structures. The cosmic ray data has different responses to each kind of interplanetary structure. This article has as objective to study cosmic ray muon and neutron signatures due to the passage of Corotating Interaction Region (CIR) in the interplanetary medium, and identify the signatures in the cosmic ray data due to these events. The cosmic ray muon data used in this work are recorded by the multidirectional muon detector installed at INPE's Observatório espacial do Sul – OES/CRSPE/INPE-MCT, in São Martinho da Serra (Brazil) and the neutron monitor installed in Newark (USA). The CIR events were selected in the period from 2001 to 2004.

## Introduction

Corotating interaction regions (CIRs) are regions of compressed plasma formed by the interaction of the slow and fast solar wind streams originated in coronal holes (Krieger et al., 1973). Their occurrence is greater during the declining and minimum phases of the 11-year solar cycle, but they may also be present at times of higher solar activity (Richardson, 2004).

In this article we show the relationship between cosmic ray modulation and CIR structures, taking into account the differences between the muon and neutron modulations due to the passage of CIRs in the interplanetary medium. We have used data from the multidirectional muon detector installed at INPE's Observatório espacial do Sul – OES/CRSPE/INPE-MCT, in São Martinho da Serra (Brazil) since March 2001, and the neutron monitor installed in Newark (USA) for this study. For more details of São Martinho da Serra's muon detector, see Da Silva et al., (2004).

This modulation has been studied for many years, typically using ground-based neutron monitors. However, the enphasis in this article is the observation made by the muon detector in order to discover if muons respond similarly to neutrons. Although the simple idea that a CIR provides an extended corotating barrier, due to the increase of the magnetic field that temporarily inhibits cosmic rays from entering the inner heliosphere, there are features of these modulation that suggest that local structures within CIRs may also play a role(Richardson, 2004).

## Corotating Interaction Region in the Interplanetary Medium

The Corotating Interaction Regions were formed when a fast solar wind stream, originate from a coronal hole of the Sun migrates from polar regions to equatorial ones and interact with a slow solar wind stream (Krieger et al., 1973). The shape of a CIR can be viewed in Figure 1.

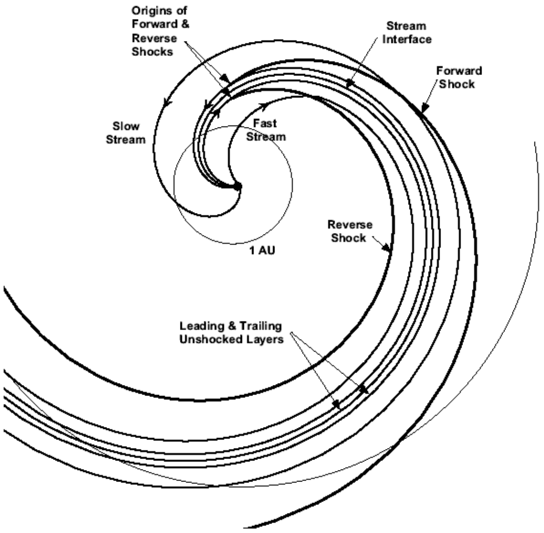

**Figure 1: Schematic view of the CIR. [N. U. Crooker and J. T. Gosling, 1999]**

A schematic view of the morphology of a CIR seen from above the north solar pole is presented in Figure 1. In the interaction between the fast and the slow solar wind streams, the fast one interacts with the slow one and a compressed region, called stream interface, is formed (Crooker and Gosling, 1999). The stream interface separates the slow solar wind stream from the fast solar wind stream. This Interaction is called "corotating" because the slow and fast solar wind streams coincide with the reference frame corotating with the Sun, together with the interplanetary magnetic field (Gosling, 1996).
The interface is typically characterized by a relatively abrupt fall in plasma density (N) and in dynamical pressure (Pd), since slow solar wind ahead of the interface is typically denser than fast solar wind, as well as by increases in the plasma proton temperature (T) and

solar wind speed (V) (Richardson, 2004). This characteristic can be viewed in the Figure2.

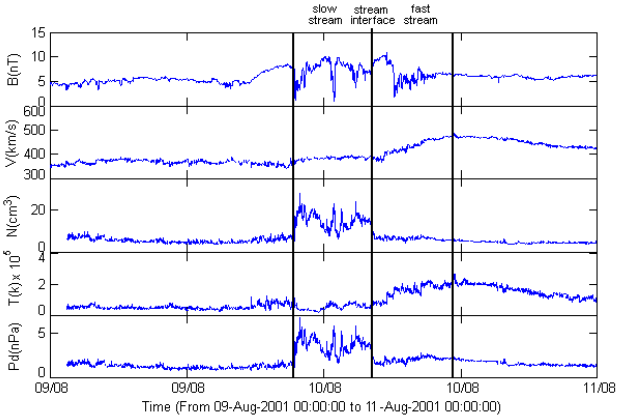

**Figure 2: Characteristics of the magnetic field and solar wind parameter data during the CIR event of the August 9, 2001.**

### The December 3$^{rd}$, 2001 CIR

In this section we present one event in order to exemplify the effects of the CIRs in the cosmic ray muons and neutrons.

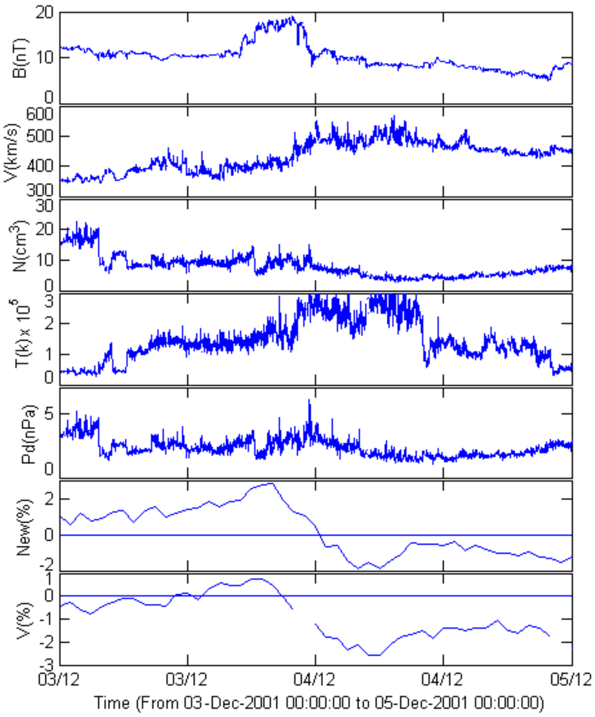

**Figure 3: CIR event of December 3$^{rd}$, 2001.**

The muon and neutron cosmic rays and interplanetary medium parameters are presented in Figure 3. From top to bottom we have the magnetic field intensity (B – nT), the solar wind speed (V – km/s), the proton density (N – cm$^3$), the proton temperature (T – K), the dynamic pressure (Pd – nPa), the percentual variation of neutron count rate of Newark's neutron momitor (New – %), and finaly the percentual variation of muon cout rate of the vertical channel of the São Martinho da Serra's muon detector (V – %). We can see clearly the muon and neutron declines during the CIR event. Similar declines were observed during most of a set of 80 other events. This decrease, due CIRs in the interplanetary medium, is, on average, higher for neutrons: 1.26% for muon and 1.94% for neutron.

### Results

All CIR events observed in the period from March 2001 to August 2004, with a total of 129 events were analyzed, Due to cosmic ray and interplanetary data problems; only 80 CIRs were used in this analysis. In Figure 4 we can see the data statistics of the events for the analyzed period.

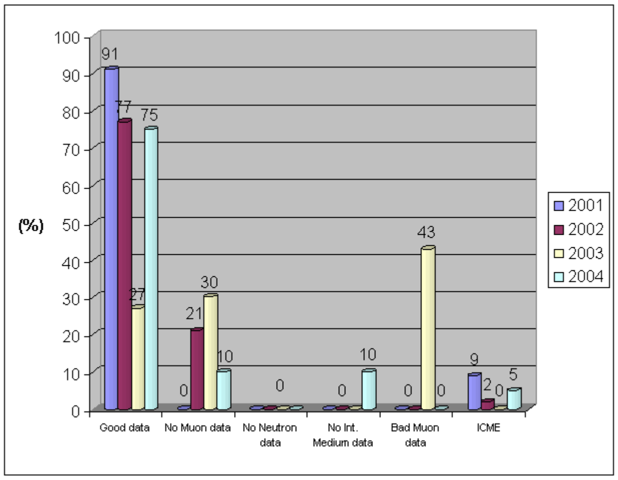

**Figure 4: Statistical analyses of the CIRs events from March 2001 to August 2004.**

Figure 4 shows that in 2003 we have a big gap in the data, due to a problem in the São Martinho da Serra's muon detector.

The relations between muon (Figure 5) and neutron (Figure 6) decreases and, from top to bottom, the magnetic field intensity - |B| (nT), the solar wind speed – V (km\s), and the magnetic field intensity times solar wind speed - |B|.V. The fit in the plot represents a linear regression of the points. The |B| data are normalized for $|B| = \frac{|B|}{5\text{nT}}$, the V data are normalized for $V = \frac{V}{400\text{km/s}}$, and finally, the |B|.V data are normalized for $|B|.V = \frac{|B|.V}{5\text{nT}.400\text{km/s}}$ in order to follow the same methodology analysis of Belov et al. (2001). The correlation coefficients are summarized in the Table 1.

**Table 1: Correlation Coefficients**

| | Muon Decrease | Neutron Decrase |
|---|---|---|
| **\|B\|** | 0.39 | 0.40 |
| **V** | 0.15 | 0.02 |
| **\|B\|.V** | 0.39 | 0.34 |

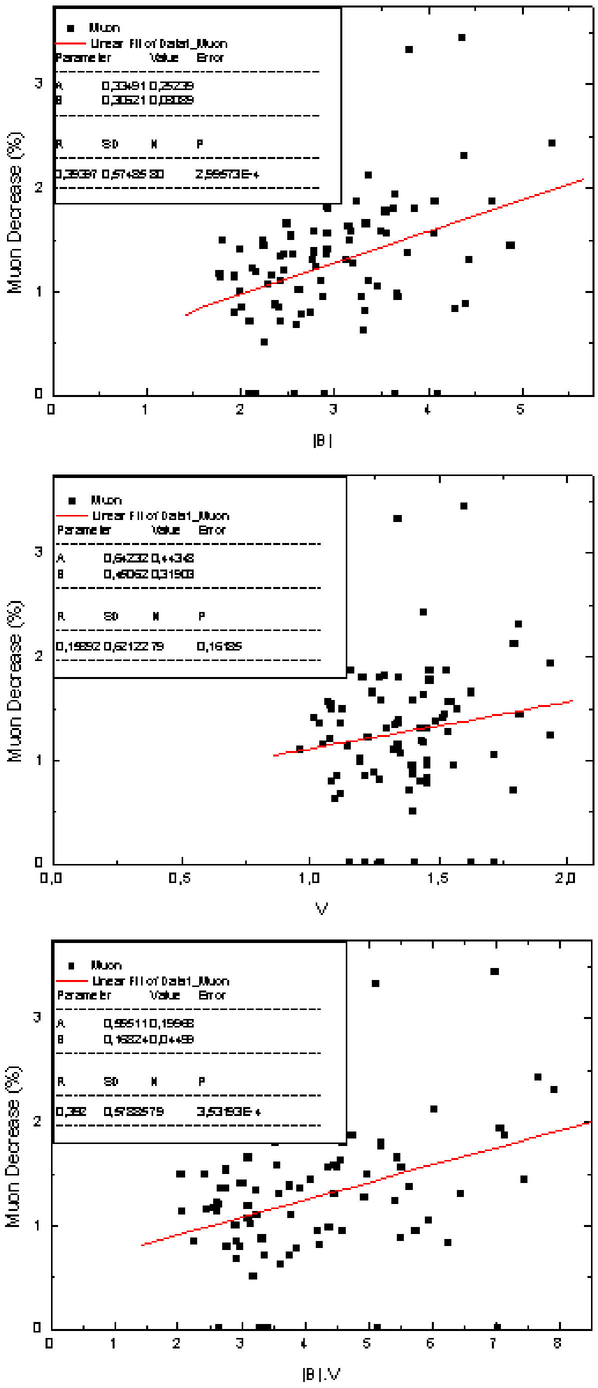

**Figure 5: Correlation between muon decrease due to CIRs and (i) magnetic field intensity |B|, (ii) solar wind speed V, and (iii) magnetic field intensity times solar wind speed |B|.V.**

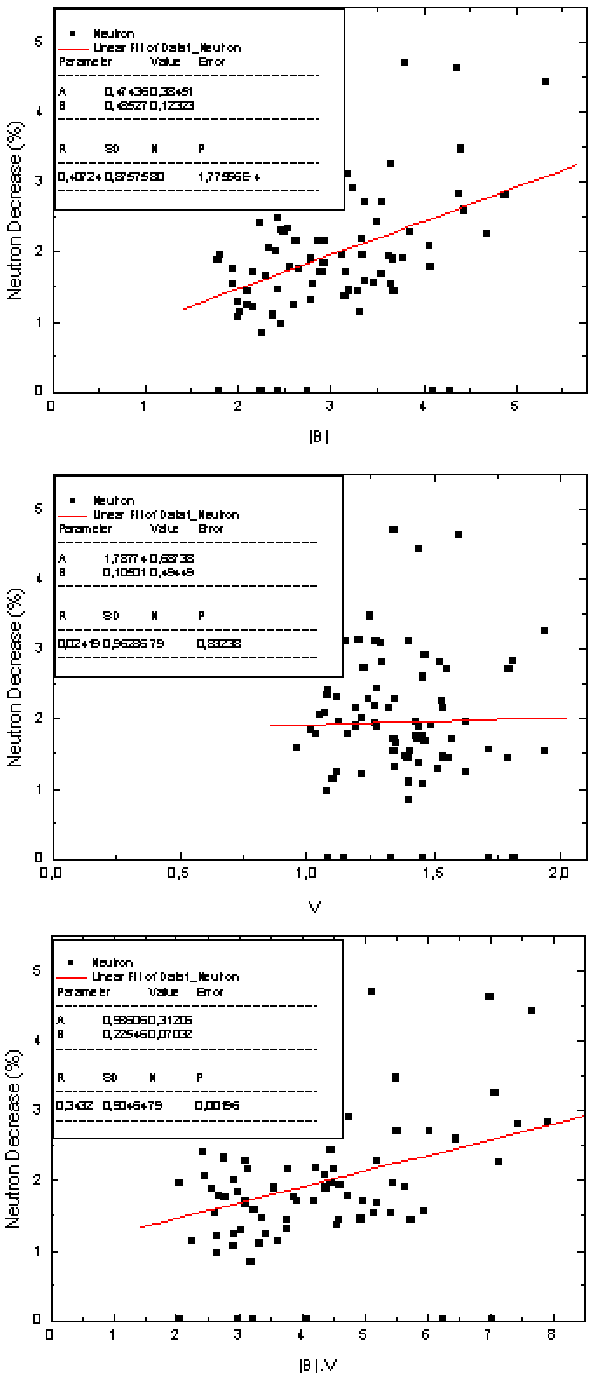

**Figure 6: Correlation between neutron decrease due to CIRs and (i) magnetic field intensity |B|, (ii) solar wind speed V, and (iii) magnetic field intensity times solar wind speed |B|.V.**

Very low correlation coefficients can be seen in Table 1, but even so, the correlation between both muon and neutron decreases and both |B| and |B|.V are better then between the decreases and V. The correlation coefficients of the Belov et al., 2001, are summarized in the Table 2.

**Table 2: Correlation coefficients for neutron decrease from Belov et al., 2001.**

| | Neutron Decrase |
|---|---|
| **\|B\|** | 0.66 |
| **V** | 0.22 |
| **\|B\|.V** | 0.70 |

Table 2 show better correlation than Tale 1, because Belov et al., 2001 used 695 events of several kinds of structures, including interplanetary coronal mass ejections, to which cosmic rays respond better as compared to CIRs. Both results agree in the sense that the magnetic field controls the decrease processes better than the solar wind speed.

## Conclusions

CIRs clearly affect Cosmic Ray population in the Interplanetary Medium in the Earth's vicinity.

All of 129 CIR events in the period from March 2001 to August 2004 were analyzed. In 19 % of the events there was no muon data available, in 15 % there was bad muon data, in 3% there were ICMEs simultaneously, and in 2% of events there was no interplanetary medium data.

During the year 2003, one of the detectors of the muon telescope was damaged committing the data. Because of this, only 27% of the data was good to be analysed in that year.

The analysis of 80 events was performed to determine the relationship between Muon and Neutron decreases and solar wind parameters during the CIRs events. The best relationships were found between both Muon and Neutron decreases and both |B| and |B|.V.

The relationships between both Muon and Neutron decreases and both |B| and |B|.V are better than between cosmic ray decreases and solar wind speed.

Most of the cosmic ray decreases ocurr after the CIRs beginning, and Muon and Neutron decrease averages are, respectively: 1.26 % and 1.94 %.

These results will be compared with the results that will be obtained through the similar analysis of the cosmic rays Forbush decreases due to interplanetary shocks and ICMEs in a future works.

Important points: -

- B was checked to be more important in causing cosmic ray declines than Vsw for both neutron and muon components.
- The average decrease of muon is lower than neutron; Since the energy (and gyro radii) of primary protons are higher for muon, this might imply that CIR affects more the lower energy (and smaller space scale) particles.

## Acknowledgments

Thanks to Word data Center for Geomagnetism – Kyoto for the Dst index, to the International Solar-Terrestrial Physics Project, through ACE teams for high-resolution solar wind data. We thank the group of research workers at the Space Weather Laboratory, to Shinshu University for technical support, to the researchers of the Bartol Research Institute, with are supported by NSF grant ATM-0000315, for the Neutron monitors data, and also to the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) for the financial support. The author would also like to acknowledge Fundação de Amparo a Pesquisa do Estado de São Paulo – FAPESP of Brazil for supporting this work, under the project 02/12723-2.

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