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Magnetic cloud properties, geoeffectiveness and cosmic ray muon decreases in the rising phase of solar cycle 24 (2009-2011)

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Abstract: The properties of magnetic clouds (MCs), their geoeffectiveness and associated cosmic ray decreases during the rising phase of solar cycle 24 (2009-2011) are studied in this work. The MC properties polarity, duration and peak solar wind parameters (solar wind speed and magnetic field strength) are determined. The geoeffectiveness of MCs is investigated in terms of the following Dst index values. Furthermore, cosmic ray decreases due to MCs and their driven shocks are studied using the muon detector data installed at Sao Martinho da Serra, southern Brazil. The results obtained in this work are compared with MC studies performed in previous solar cycles.

Keywords: magnetic clouds, cosmic ray decreases, geomagnetic storms, solar cycle

1 Introduction

Magnetic clouds (MC) are a subset of the interplanetary remnants of coronal mass ejections (ICMEs) that have the following characteristics: (1) large-scale and smooth magnetic field rotations; (2) enhanced magnetic field magnitude; and (3) decreased plasma temperature/plasma beta ([1];[7]). MCs can be classified acccording to the IMF Bz and By rotation. For Bz polarity, they can have a rotation from north to south (NS), south to north (SN), purely south (S) or purely north (N) components. MCs and their driven shocks have large effects on magnetospheric activity, and they are one of the main causes of intense geomagnetic storms ([6]; [7]; [8]) . Furthermore, large cosmic ray decreases are usually observed after the passage by Earth of MCs and their sheaths ([2];[13];[8]).

It is the aim of the present paper to study MC properties during the rising phase of solar cycle 24 (2009-2011). The main parameters of MCs are studied. Furthermore, the geoeffectiveness, in terms of magnetic storms observed with the Dst index, and the cosmic ray (muons) decreases at ground level are studied.

2 Data and Methodology of Analyses

MCs have been selected using the three definition criteria (see Introduction). Solar wind data were obtained from ACE ([11]) plasma and magnetic field instruments (www.srl.caltech.edu/ACE/). The Dst index [12] was obtained from the WDC Kyoto-Geomagnetism (swdcwww.kugi.kyoto-u.ac.jp/). The cosmic ray muon data are from the muon detector installed at Southern Brazil.

The cosmic ray muon detector installed at southern Brazil is part of the Global Muon Detector Network (GMDN) ([4]). The place where it is installed is the Southern Observatory at Sao Martinho da Serra (SMS), Rio Grande do Sul. The altitude is 488 m, the latitude is 29.44^oS, the longitude is 53.81^oW. The geomagnetic cuttoff rigidity is 9.3 GV. The average pressure is 950 hPa.

The cosmic ray detector is a muon telescope (scintillator). It was installed in March 2001 with an area of 4 m^2, then upgraded to 28 m^2 in January 2006, and again upgraded to 32 m^2 in September 2012.

For this study, the period from 2009 to 2011, when the muon detector had an area of 28 m^2, has been selected. This period corresponds to the rising phase of the solar cycle 24. During this period, 17 MCs were selected from the ICME list published in([10]). For the SMS muon telescope, only the vertical channel is selected for analyses. The muon counts are transformed in relative variation, or percentage deviations, in relation to the annual average.

3 Results and Discussions

Figure 1 shows an example of the MCs studied in this work. Panels are solar wind speed, proton density, proton temperature, magnetic field magnitude, Bx, By and Bz components, Dst index and SMS vertical channel counts, in relative units. The MC boundaries are marked with dotted lines. The cosmic ray muon decrease is indicated with a double arrow in the bottom panel. This MC occurred from 0500 UT 28 May 2011 to 2100 UT 28 May 2011 (day of year 148). Its duration was of 16 hours. No interplanetary shock was seen preceeding it. The peak magnetic field magnitude was 13.0 nT and the peak solar wind speed, 538 km s^{-1}. It can be seen that the MC shows a south to north rotation in Bz component, with By mainly negative. The peak south Bz (Bs) was -10.5 nT. There was a moderate geomagnetic storm caused by the south Bz part of this MC, with a peak Dst of -91 nT. The muon decrease is indicated with the double arrow bar in the bottom panel. For this MC, the decrease was -0.48%.

Figure 2 shows an example of a MC preceded by shock on day 35 2009 . The panels are the same as shown in Figure 1. The shock is marked with a solid line, and the MC

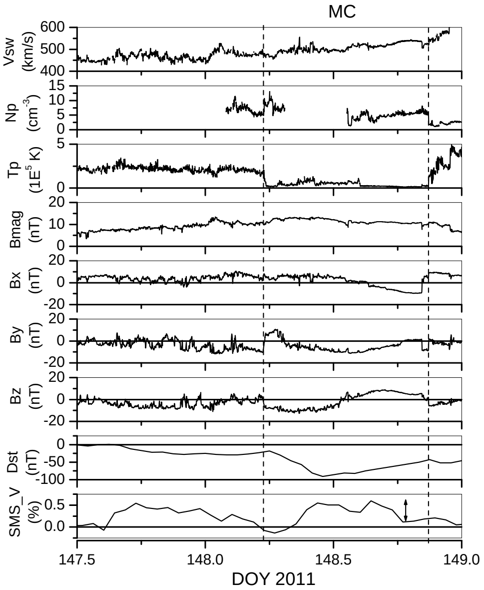

Fig. 1: MC during 28 May 2011. Solar wind parameters, Dst index and vertical channel relative counts from SMS detector are shown. MC boundaries are marked with dashed lines. The muon decrease is indicated with a double arrow.

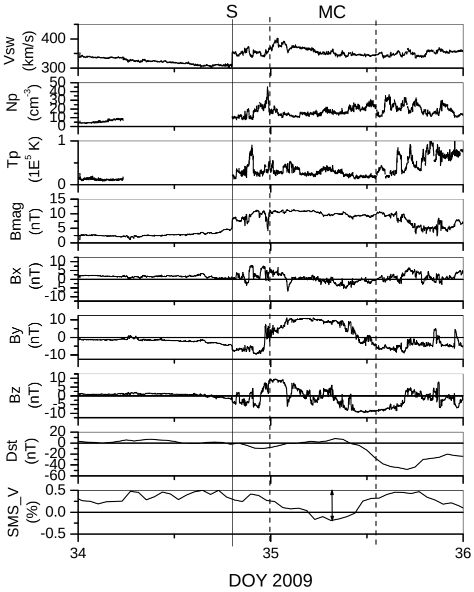

Fig. 2: MC during 04 February 2009. Solar wind parameters, Dst index and vertical channel relative counts from SMS detector are shown. MC boundaries are marked with dashed lines and the shock with solid line. The muon decrease is indicated with a double arrow.

boundaries with dotted lines. Again, the cosmic ray muon decrease is indicated with a double arrow in the bottom panel. The shock occured at 1908 UT on 03 February. The MC oocurred from 0000 UT 04 February to 1600 UT 04 February 2009, with a duration of 16 h. The MC polarity was of NS type. The peak magnetic field magnitude was 11.0 nT and the peak solar wind speed, 349 km s^{-1}. It can be seen that the MC shows a north to south rotation in Bz component, with By mainly positive. The peak south Bs was -9.3 nT. There was a weak geomagnetic storm caused by the south Bz part of this MC, with a peak Dst of -48 nT. The muon decrease is indicated with the double arrow bar in the bottom panel. For this MC, the decrease was -0.61%.

During the rising phase of solar cycle 24, 17 MCs were observed: 2 MCs in 2009, 6 MCs in 2010 and 9 MCs in 2011. Sunspot number annual average for these three years was 3.1, 16.5 and 55.7. As the last minimum was in 2008, it can be noted an increase in the MC occurrence with rising solar activity, as observed for previous cycles (e.g, [7]; [10]). From the 17 MCs, 11 were preceded by driven shocks and 6 MCs were not. Thus most of MCs are fast enough do drive an interplanetary shock wave.

In terms of this Bz polarity, 5 MCs were of SN, 7 of NS, 3 of S and 2 of N types. Thus the 12 bipolar MCs were predominantly of NS type (58%) against 32% of SN type. It was observed that SN MCs dominated for the 1973-1978 interval, NS MCs for 1983-1988, and SN MCs again for 1993-1998 ([7]). Thus it would be expected that NS MCs would dominate this cycle. It seems that the MC polarity varies in response to changes in the magnetic structure of their solar region. The forward MC fields are controlled by the polarity of the global solar magnetic field, while the inclination of the coronal streamer belt controls the clouds axial symmetry. The orientation of the MC field is the same as the global dipole solar magnetic field, which changes direction every 11 year. (The full solar cycle is 22 years).

Table 1 shows average parameters for MCs. The cosmic ray muon decrease is indicated as ΔI . It can be observed that MCs have an average duration of 16.1 hours, and average peak value of the IMF magnitude of 14.7 nT, IMF Bs component of -7.6 nT and solar wind speed of 457.3 kms^{-1}. The associated geomagnetic activity had an average peak Dst of -52 nT. The average cosmic ray decrease noted in the vertical channel of SMS muon detector was -0.83 %. These values are lower than the long-term average solar wind parameters and Dst for 1973-2001, of B$_p$ = 15.5 nT, Vsw$_p$ = 485 km.s−1, Bs$_p$ = -10.5 nT, and Dst$_p$ = -93 nT ([7]). Note that Dst average peak values for the cycle 24 are much lower, about 55% of the longer interval.

It was observed that 1 MC was followed by an intense storm, 8 MCs by moderate storms, 3 MCs by weak storms and 5 by a geomagnetically quiet period. Thus the geoeffectiveness (percentage of MCs followed by intense or moderate geomagnetic storms) was of 52.9%, i.e, around half of MCs were followed by intense or moderate geomagnetic storms. For the MC preceded by shocks, the geoeffectiveness is much higher, 8/11 (72%). For the slow MCs only 17% were geoeffective. For a longer interval, 1973-2001, the geoeffectiveness of MCs were found to be 77.2 % ([7]). When considering MCs associated with shocks, the geoeffectiveness is higher, 81% (([6]). Although we do not have the statistics of slow MCs for previous cycles, in the current cycle the proportion of slow is considerable, around 1/3 of MCs. thus reducing the overall geoeffectiveness of MCs.

For MCs that did not drive shocks, the cosmic ray decrease was lower, -0.71%, ranging from -0.40% to -0.96%. For MCs preceded by shocks, the decrease was -0.90%, ranging from -0.37% to -1.5%. This is coherent what has been observed. In a study using neutron monitor data ([13]), it was found a 2.5 % decrease of cosmic ray intensity asosicated with MCs that are preceded by as shock, but only a 0.5% decrease is associated to the MC itself.

Figure 3 shows the scatter plot between the B$_p$ and the

Parameter and statistics	Average	SD	Median
Duration (h)	16.1	6.9	16.0
B_p (nT)	14.7	4.1	13.6
Vsw_p (km.s^{-1})	457.3	11.7	429.0
Bs_p (nT)	-7.6	4.4	-6.1
Dst_p (nT)	-52.0	35.1	-51.0
Δ I (%)	-0.83	0.34	-0.80

Table 1: Magnetic cloud solar wind parameters, Dst and cosmic ray muon decrease (Δ I)

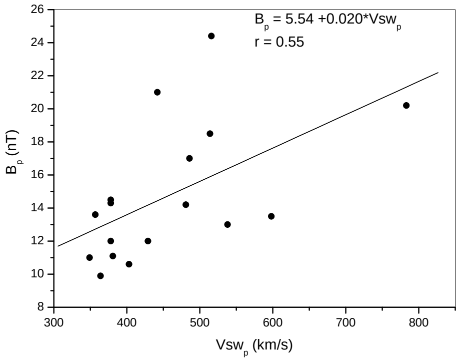

Fig. 3: Scatterplot between B_p and Vsw_p. The correlation coefficient and linear fit equation are also shown.

Vsw_p. The correlation is r = 0.55. The equation is showed in the figure. The proportionality coefficient is $B_p \sim 0.020$ Vsw_p. This result can be compared with previous studies. For MCs during solar cycle 23, it was found a correlation of r = 0.6, against $r < 0.3$ for non-clouds ([10]). For a longer interval, 1973-2001, the correlation was lower, r = 0.35, but the proportionality coefficient the same, $B_p \sim 0.020$ Vsw_p ([7]). Other studies have found $B_p \sim 0.047$ Vsw_p with a correlation of r = 0.71 ([9]), and $B_p \sim 0.024$ Vsw_p with a coefficient of r = 0.60 ([3]).

Figure 4 shows the correlation between B_p and the Vsw_p, Bs_p and the product between Vsw_p and Bs_p (equivalent to the dawn to dusk interplanetary electric field Ey component). It can be seen that correlation is higher for Dst-Vsw_p.Bs_p Ey (r = 0.85) and for Dst- Bs_p (r=0.71) than for Dst- Vsw_p (r = 0.53). This is expected since geomagnetic activity depends more on the IMF Bs component than on solar wind speed.

Figure 5 shows the correlation between ΔI and the solar wind parameters. The correlations are 0.23 for ΔI and Vsw_p and ΔI and B_p, and higher, r = 0.30, for ΔI and the product between B_p and Vsw_p.

From the linear correlation between cosmic ray variation and IMF magnitude, the propotionality coefficient of -0.019%. B_p. Thus a 25 nT field would cause a -0.47% decrease in muons. This contrasts with results presented by ([2]), who has found a decrease of 6% in IMP8 Guard cosmic ray data, and 3% in neutron monitor data for a field of 25 nT.

For muon decreases due to corotating interaction regions (CIRs),the coefficient correlations were 0.15 for ΔI and Vsw_p , r = 0.39 ΔI and B_p, and higher, r = 0.39, for ΔI and the product between B_p and Vsw_p ([5]). The decrease of muons was lower than for neutron monitor cosmic ray data (1.26% and 1.94 %, respectively) ([5]).

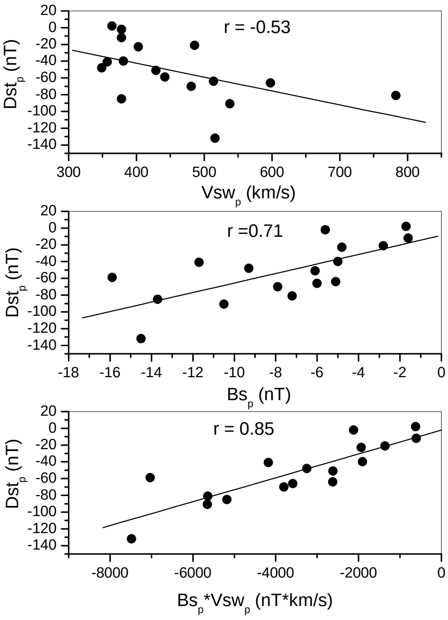

Fig. 4: Correlation between Dst_p and Vsw_p (top panel), Dst_p and Bs_p (middle panel), and Dst_p and Ey_p (bottom panel).

4 Summary and Conclusions

MCs properties, geoeffectiveness and cosmic ray decreases in the rising phase of the solar cycle 24 (2009-2011) have been studied in this work. It was found that:

- The occurrence of MCs increase with solar activity.
- MCs have an average duration of 16 hours, and average IMF magnitude of 14.7 nT, peak southward component of the magnetic field -7.6 nT, and peak solar wind speed of 457.3 (km.s^{-1}).
- The relation between B_p and Vsw_p was confirmed, with a proportionality coefficient of $B_p \sim 0.020$ Vsw_p .
- Most of MCs were found to drive a fast shock (around 2/3).
- For the MCs that showed a bipolar profile in Bz (around 2/3), most were of the NS type, as expected according to the 22 year solar magnetic field variation.
- The average peak Dst after MCs was -52.0 nT. The percentage of MCs followed by intense or moderate geomagnetic storms (geoeffectiveness) is 52.9%, much lower than previous cycles.
- When considering only MCs that drive fast shocks, the geoeffectiveness is 72.0%. This is in agreement with previous studies that showed enhanced geoffectiveness for fast MCs.
- The average muon decrease after MCs. was found to be -0.83%. The correlation between muon decrease and solar wind parameters was found to be higher for the product between B_p and Vsw_p than for each solar wind parameter separately.

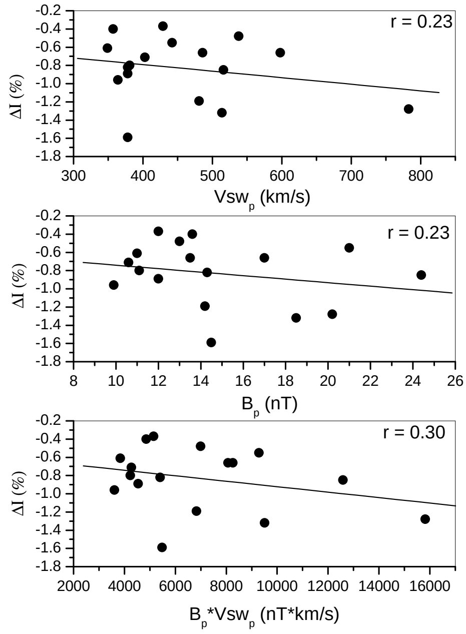

Fig. 5: Correlation between ΔI and Vsw$_p$ (top panel), ΔI and B$_p$ (middle panel), and ΔI and B$_p$.Vsw$_p$ (bottom panel),

- For a MC with 25 nT, the expected muon decrease is -0.47%, which is much lower than what is observed for neutron monitor data, about -3% ([2]).
- MCs that drive shock causes larger muon decreases (averageo of -0.90%) than MCs without shocks (average of -0.71%).

It can be concluded that MCs that drive fast shocks are more geoeffective and cause larger cosmic ray muon decreases. It would be interesting to study MCs over this whole solar cycle 24 to verify if the last deep minimum in solar activity caused a different behavior in MC properties as compared to past solar cycles.

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