On the relationship between interplanetary magnetic field and cosmic ray flux over Antarctica

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Abstract. The total Interplanetary Magnetic Field (IMF) probed by the ACE Satellite during the years 1997-2004 has been used to investigate the corresponding changes observed in the cosmic Ray Flux (CRF) during the same period at Mac Murdo (77.9° S, 166.6° E) in Antarctica. The analysis unambiguously shows that the CRF is predominantly influenced by the total IMF and occasional fluctuations of the CRF perhaps are associated with the Galactic cosmic ray flux changes. However, data on the absolute changes occurring with the Galactic CRF are not known to exist from any independent measurements outside the heliosphere. The data from ULYSSES satellite on high energy alpha particles (Z>=3 and 26-173+ MeV/n) of solar cosmic ray is found to be positively correlated to the CRF flux measured at ground to a large extent. Further, it is to be mentioned that the earthbound phenomena at lower atmosphere like cloud formation, thus, related Climatological effects although seem to have a causal relationship with the CRF need to be more closely examined since the penetration of CRF is found to be significantly depend on the total IMF conditions prevailing just outside our earth at Magnetopause distances.

Index Terms. Cosmic ray flux, Earth's climate, interplanetary magnetic field.

1. Introduction

During recent few decades the level of CRF arriving earth's lower atmosphere is being noticed to be an important parameter and it has become increasingly an important factor to understand, since, its intensity changes at troposphere heights seem to have causal relationship with the climate conditions of our earth. The changes occurring in intensities of CRF perhaps keep influencing the earth's lower atmospheric phenomena such as climate through its ion production processes (Usoskin et al., 2004) that are essential for cloud formations (Tinsley, 2000). This aspect is being discussed in the recent years most dramatically and efforts have been made to make long records of many such CRF detecting facilities at several locations on the globe (http://www.env.sci.ibaraki.ac.jp/database/).Most importantly, the penetrating efficiency of cosmic ray particles and hence the ion production at the lower atmosphere heights depend upon the cosmic ray cut-off rigidity for a given latitude and longitude. Further the solar activity also influences the penetration threshold energy of the cosmic ray particle at interplanetary medium distances by the presence of intervening interplanetary magnetic fields which is far a distant process compared to the earth's lower atmospheric ion production by cosmic ray particles. However, it remains an important process since the penetration of comic ray particles seem to depend primarily on interplanetary magnetic field. Also the cosmic ray intensity changes from place to place due to the presence of secularly varying earth's magnetic field and hence the changes found with cut-off rigidity limits (Bhattacharyya and Mitra, 1997). It appears from our study that during low solar activity, the Galactic cosmic rays can penetrate without much difficulty and perhaps could be found in larger proportions in comparison to the solar cosmic ray particles detected by the earth bound sensors. Whereas during high solar activity the Galactic cosmic ray intensities are significantly attenuated by increased interplanetary magnetic filed conditions. This is due to the ejection of plasma from solar surface and related frozen-in field deflecting forces that are associated with it in terms of energetic solar winds (Partamies, 2004). The interplanetary space environment is quite different compared to the near earth space environment due to the presence of earth's magnetic field which is shielding the inner atmosphere from hazardous high energy particles to a certain extent. However, the solar high energetic events such as Coronal Mass Ejections (CME's) and solar flare events (Tsurutani et al., 2003) convolve enormous amount of energy over the normal flow of energy in terms of high energetic particles that are associated with the magnetic field being frozen-in within the plasma. Hence, they can significantly disturb the earth's magnetic field by the penetration of high energetic particles into the magnetosphere and generate various disturbances on the earth's quiet time parameters, especially on ionospheric current systems (Rajaram et al., 2002; Sizova et al., 2003; Lima et al., 2004). In the case of extremely energetic events they can even be potentially hazardous to the surface level electrical distribution networks and long gas pipe lines and satellite communication systems, surface level temperature increase and satellite's hardware (http://www.mpelectric.com/storms/). These types of events are more common during solar maximum rather at solar minimum but can't be completely exempted (Srivastava and

Venkatakrishnan, 2004). On the other hand, the solar activity and its reverse relationship with the CRF for several solar cycles have been shown to occur (Marsh and Svensmark, 2000) and further it is discussed that the efficiency of cloud formation has underlying relationship with the amount of CRF arriving at the cloud forming heights by producing ions. In contrary to this there is also an argument that the cloud formation has better correlation with the solar irradiance rather than with the cosmic ray flux (Kristjansson et al., 2002). However, we have to characterize the modulation mechanisms those operate on the amount of cosmic ray particle arriving earth's lower atmosphere to understand its effects on climate before being conclusive of any such relationships by either of these arguments. Hence in order to understand such process in detail as a first step we have made an attempt to understand the relationship of interplanetary conditions in modulating the CRF intensities at ground level and henceforth to work on the climatic effects of CRF. The data are chosen corresponding to a high latitude station so that the changes observed will have a direct bearing on the interplanetary conditions rather than the cosmic ray cut-off rigidities. The cut-off rigidities vary from place to place on the earth within ±50 degrees most considerably, whereas above this latitude it does not seriously differ since the earth's magnetic filed lines are inclined and favor for the penetration of high energy cosmic ray particles to a large extent. Further, it becomes less important as far as high energy cosmic ray particles are concerned (>1GV). Hence, in this paper we present the ground based CRF changes at a high latitude station and its plausible relationship with the interplanetary total Magnetic field measured by the ACE satellite corresponding to the years 1997-2004 of the solar cycle which is just being in its completion phase.

2. Data

The CRF data collected by a neutron monitor at Mc Murdo a high latitude station, located at Antarctica has been used. The neutron monitor collects samples with an interval of 60 minutes. The neutron monitors are most sensitive to the low energy (1-20 GV) portion of the cosmic ray energy spectrum. There are about 24 samples for each day during the years 1997-2004 accounting for 64, 272 hours of data since 1st Sep 1997 which are used in this study. The total IMF data collected by ACE satellite since its launch (1st Sep 1997) until 2004 providing data at an interval of 4 minutes resulting in 9.2 million samples have been presented in this study.

3. Method

In order to understand the effect of solar activity on CRF intensity the recent solar cycle data has been chosen to represent the low/high activity of the Sun. This has been done using its corresponding data on total IMF field strength. In the first step both CRF and total IMF has been made to contain equal time (hourly) resolution by extracting the total IMF data samples such that it becomes an hourly data rather than 4 min resolution to match with the CRF data resolution. The absolute values of the data have been used to derive derivative values with time for the period of 1997-2004 for both the parameters which provide only the changes over the trend which was being observed over this period. The trend and the fluctuations part are separately compared in order to understand the long/short term relationships. The derivative data in a sense provides a high pass filtered data with the lowest period allowed being an hour. Nevertheless, the trend is obtained by applying a running average of 648 hrs on total IMF data. The number of hours is chosen such that the 27 day solar variability does not present in the estimated trend data which ensures that the variability due to the Sun's rotation does not introduce any difficulty to our understanding. Occasionally occurring erroneous values in the total IMF data set usually of a few minutes have not been included in the analysis; they had been left as data intervals, however, while converting the series for acquiring hourly data there are no intervals in the data since the intervals are filled up with the interpolated data.

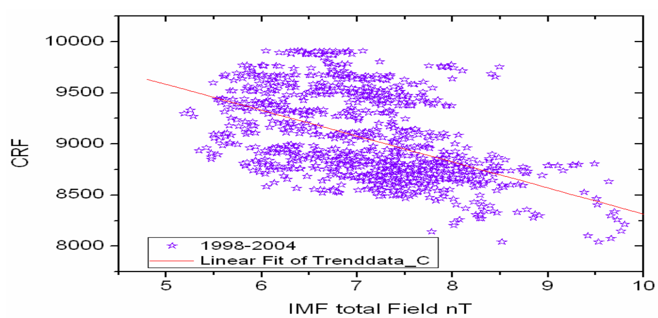

Fig. 1. Correlation between the trend of CRF and total IMF using the hourly data.

4. Discussion

The hourly absolute values of total IMF and its running average for 27 day are seem to fluctuate about 7-10 nT. The hourly values often fluctuate above 20 nT. Remarkably at certain instances of time upto 75 nT. These points perhaps are due to the storm occurrences. However, we did not distinguish such events since it will have its corresponding counter effect on CRF changes and still we could manage to obtain a parameter which would show the behavior of CRF during such surge effects. Also it is inferred that trend of 27day average of total IMF showing an increase from 1998 to 2004. Similarly the absolute count of the CRF and its trend by a linear fit seem to decrease during the same period. The correlation study made for the absolute values of CRF versus and the total IMF has shown little correlation or no correlation. Whereas when the trend for each parameter is plotted against each other (bottom panel) it has shown an unambiguous reverse relationship (Fig.1). In order to understand their short period fluctuations the derivatives (shown in Fig.2) of each parameter are taken (equivalent to high pass filtering); it is found that they follow certain kind of distribution. Only alternative year of data on this aspect is plotted so as to minimize the number of plots. The fluctuations in CRF follow a distribution which is more or less like a Gaussian curve (Fig.3). Similarly the distribution of the high pass filtered data of the total IMF has shown that distribution of these parameters seems to follow an exponential rise and a fall between -5-+5 nT. The ratio of these two parameters (R-factor) are shown in Fig.4, and its distribution found to behave nearly the same manner as the total IMF rather than the distribution of CRF but somewhat more steeper during both up leg and down leg of the distribution.

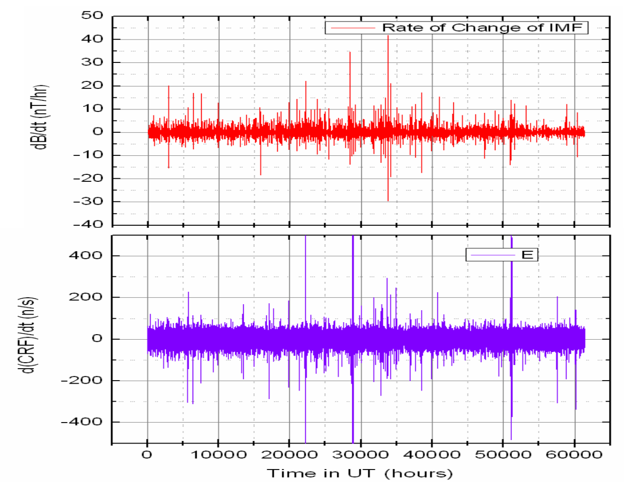

Fig. 2. The time derivatives of the CRF and total IMF

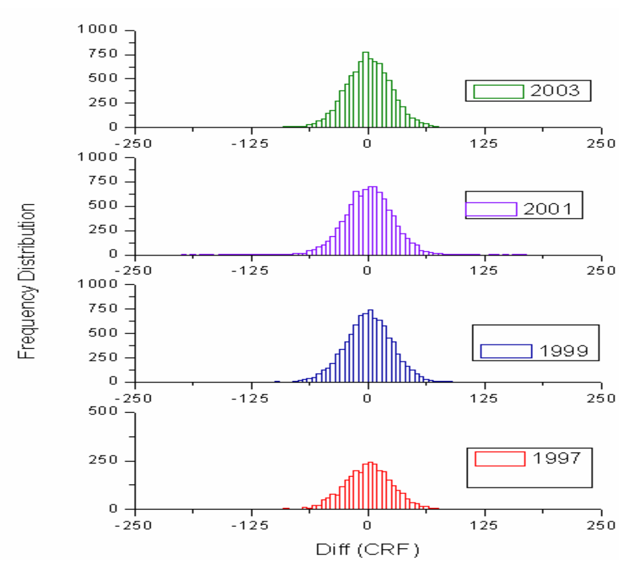

Fig. 3. Distribution of fine temporal changes observed with the CRF.

The Fig.5 shows the behavior of R-factor with the total IMF. It is to be mentioned that the plot was restricted between -1 to +1 since 99% of the points are within this range and a few points beyond this range are seen to be of no significance. The linear fit of the data shows the R-factor itself keeps increasing during the years 1998-2004, however, the increase is found to be significantly small by about three orders of magnitude. Further the fluctuations in R-shown to have a remarkable distribution with the total IMF. It implies that the cosmic ray changes are in fine equilibrium with the interplanetary magnetic field when the changes of the total IMF field are about 5-6 nT. Below this magnitude the cosmic ray changes are very rapid unlike it is seen when IMF magnitudes are above this range. When the magnitudes of total IMF are above this range the changes observed with the cosmic ray intensity are much steadier in bringing the R-value much smaller. The values of R- recover more steadily than its uptrend which is seen when the total IMF magnitudes are below this range (<5-6 nT). It is somewhat quite interesting to evidence such an equilibrium point of R and total IMF. The physical significance of that particular region of R perhaps indicates that when the total IMF values are around 5-6 nT the cosmic ray intensity changes are also in accordance with it, implying interplanetary cosmic ray particle pressure is just balanced by these values of the total IMF. Whereas when the total IMF value further increases the corresponding changes of CRF are found to associate its influx to the solar wind itself and start drifting to non-equilibrium conditions. It is inferred that as the total field start increasing from zero the R-factor starts rising rapidly and reaches its peak about 5-6 nT and when the total IMF starts increasing further the R-factor starts decreasing more or less linearly but rather slowly. In fact the R-factor does show another interesting feature that is the changes of the CRF with respect to the total IMF. For example, in Fig.5 the points above zero and below have inherent meanings that are in phase and out of phase respectively. The shape of the distribution about the zero-line both above and below seems to be closely identical regardless of their phase relationships.

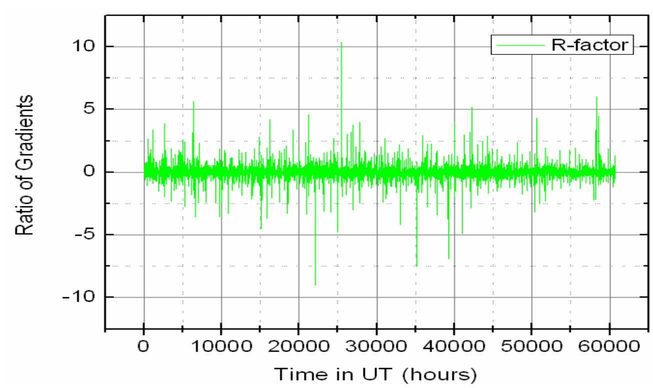

Fig. 4. Temporal behavior of R-factor during 1998-2004.

This implies that the CRF intensity changes are completely due to the repulsive nature of the enhanced total IMF conditions regardless of their polarity that we normally conjecture with the earth's magnetic field. This is quite understandable because, as high energetic plasma cloud is ejected from the Sun which is associated with the strong frozen-in magnetic fields and these fields repel the surrounding cosmic energy particle matter away from its region regardless of their magnetic field configuration. Further, in order to understand the role of cosmic ray flux received from solar disk by the earth's atmosphere the data from Ulysses satellite which was just in the Sun-Earth-Aphelion line of the satellite facing the same surface of the Sun during 1998 has been utilized. The relationship of Ulysses data with the solar cosmic ray flux in Fig. 6 have

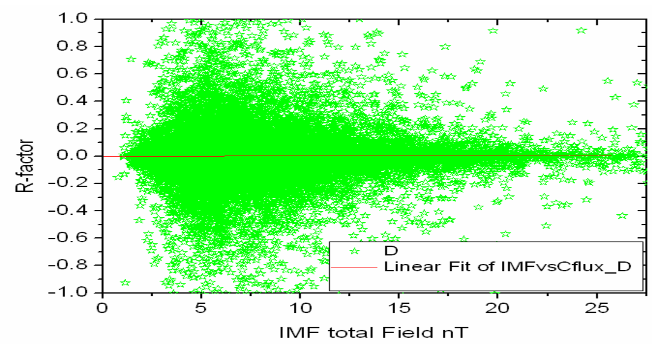

Fig. 5. Behavior of R-factor with the total IMF

shown a good positive correlation between the CRF and high energetic particle detected by the Ulysses satellite orbiting the Sun. It appears that the long term trends of the CRF intensity are predominantly due to the solar cosmic ray emission (during solar maximum). Interestingly, when the Sun remains less active (during solar minimum) the Galactic cosmic ray penetrates deep in to the atmosphere and contributes more to the measured cosmic ray intensities at mean sea level heights. However the relative strength has not been found since such data set is not made available hitherto. Nevertheless, from our analysis, we would advocate that when the total IMF strengths are less than 5 nT one would perhaps assume that (based on R-factor structure) the cosmic ray flux measured is mostly due to the Galactic cosmic ray sources. Further, it is to be mentioned that when the total IMF field values are exceeding 5 nT it would indicate that the Sun starts building up its activity and hence solar cosmic ray flux also contributes to the cosmic ray particle measured on earth. These particles entering at interplanetary boundaries suffer greater attenuation due to its

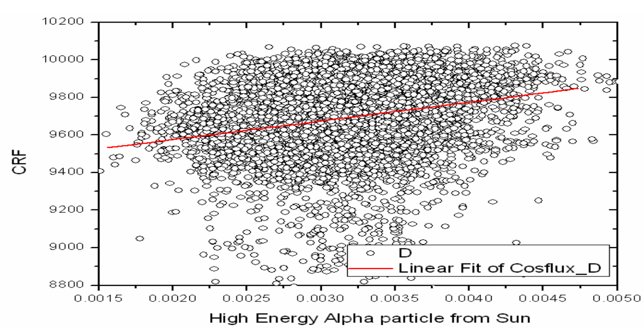

Fig. 6. High energy alpha particle flux from ULYSSES space craft versus the cosmic ray flux measured at ground during 1998.

own field frozen-in solar wind at increased level of activities; hence, we see the right arm of the R-factor as an extended one with much smaller values. It reveals that when stronger the value of total IMF occur greater the attenuation that takes place for the solar cosmic ray particles. Fig.7 is drawn in order to understand that the relative correlation of CRF with the total IMF during solar maximum as well as for solar minimum so as to bring out if any contrasting features exists. It is expected that they should correlate less or do not correlate at all with the total IMF during solar minimum and best correlate during maximum period. To our surprise, the

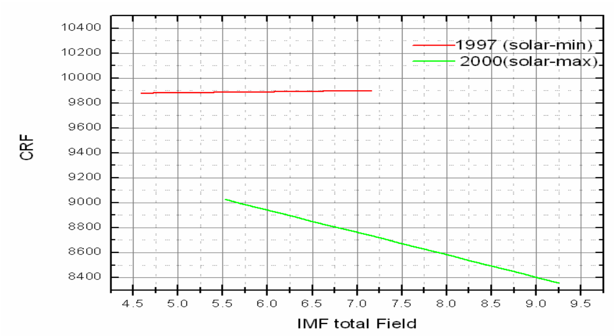

Fig. 7. Relationship between CRF and total IMF during a solar Maximum and solar Minimum.

figure indeed has shown such a straightforward relationship substantiating our findings. These things imply that the final quantity of cosmic ray particle flux measured on the earth those are available for the production of ions has several controlling mechanisms and need further investigation on the individual flux quantities produced by Galactic, Solar, and Anomalous cosmic ray sources in order to resolve the relative role of the above sources on climate.

5. Conclusion

The CRF intensity measured at ground level is predominantly diminished by the increase in total IMF magnitudes regardless of their polarity. Secondly the Interplanetary cosmic ray particle pressure seem to be balanced by the total IMF of about 5-6 nT and while any value less than this is expected to provide an entry for the Galactic cosmic ray particles. Solar cosmic rays seem to dominate the Galactic cosmic ray intensities during solar maximum epoch by expelling the Galactic cosmic rays much more efficiently at total IMF magnitudes above 5 nT. During the solar minimum (when the total IMF is <5-6 nT), the Galactic cosmic rays remain less influenced by the interplanetary magnetic fields and it would perhaps provide a measure of Galactic cosmic ray shower particles entering Earth's atmosphere without much reduction in its number density.

Acknowledgements. We thank Bartol Research Institute for providing cosmic ray flux data of McMurdo station located at Antarctica in the World Wide Web which has enabled us to do this work. The Bartol Research Institute neutron monitor program is supported by the United States National Science Foundation (NSF) under grant ATM-0000315. We also thank NASA also for providing the ACE satellite data on total IMF presented in this study.

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