J. Astrophys. Astr. (2019) 40:26
https://doi.org/10.1007/s12036-019-9593-2

Study of the cosmic ray intensity in relation to geomagnetic storms and solar interplanetary parameters for solar cycles 21 and 23

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MS received 4 February 2019; accepted 22 May 2019; published online 15 June 2019

Abstract. This paper comprises the comparative study of the behavior of CRI with geomagnetic storms, southward component of IMF, i.e. $|Bz|$, IMF B, solar wind speed (V) and $V \cdot |Bz|$ for two consecutive odd solar cycles 21 (1976–1985) and 23 (1996–2008). Our examination arrived at an interesting result that the strongest decrement in CRI occurs around the same time when Dst achieve their minima. The correlation coefficient of Dst with CRI is observed high for both the solar cycles. We have moreover contrasted the profiles of CRI with B, $|Bz|$ and V and came to the resolution that the strongest increment in B, $|Bz|$ and V happens on the same day when CRI reaches its minimum peak. During the study of CRI with the solar wind speed, we have observed odd behavior for the year 1977 and 2003 with a time lag of one day. We have also found that CRI is highly anti-correlated with $V \cdot |Bz|$ when contrasted with V or $|Bz|$ alone. The correlation coefficient between CRI and $V \cdot |Bz|$ is found to be high and the same (-0.8) for the solar cycles.

Keywords. Cosmic ray intensity—solar wind velocity—interplanetary magnetic field—geomagnetic storms.

1. Introduction

Cosmic rays are highly energetic radiations and the study of these radiations and their association with the solar-interplanetary conditions is done by many researchers (Forbush 1938; Joselyn *et al*. 1986). The interplanetary magnetic field (IMF) plays an essential role in regulating the cosmic ray intensity (CRI) of the heliosphere. Ahluwalia (2013) and Usoskin *et al*. (2004) stated that the variation in CRI produces an adverse effect on the various atmospheric phenomena and is also responsible for the formation of cloud. Tinsley (2000) and Partamies (2004) found that the intensity of cosmic rays attenuated by increased interplanetary magnetic field conditions.

The solar wind is a flow of charged particles and the passage of these solar winds cause changes in the solar atmosphere. When solar wind with high speed reaches the Earth, the geomagnetic field is compressed which results in the variation of geomagnetic field. This geomagnetic imbalance is referred to as the geomagnetic storm (GS). The fundamental reason for this sort of disturbance is the coupling of high-energy particles with the magnetic field of the Earth. So, we can simply define GS as a perturbation in the magnetic field of the Earth. The fundamental property of a geomagnetic storm is the creation of ring current and the prime reason for the growth of ring current is the injection of particles into the inner magnetosphere from the magnetotail. The Dst is the most commonly used geomagnetic index that provides a quantitative measurement of the magnetic field created by this ring current. Dst index has been introduced by Sugiura and Kamei (1991) and is the conventional measure of ring current intensity and energy, and is also used to indicate the severity of GSs. Wanliss and Showalter (2006) measured it in nanotesla.

Shrivastava and Jaiswal (2003) studied the effect of flare-associated streams and co-rotating streams on CRI and reported that both the streams produce similar kind of decrease in CRI while contrary to this, Yadav *et al*. (1994) and Badruddin (1996) reported

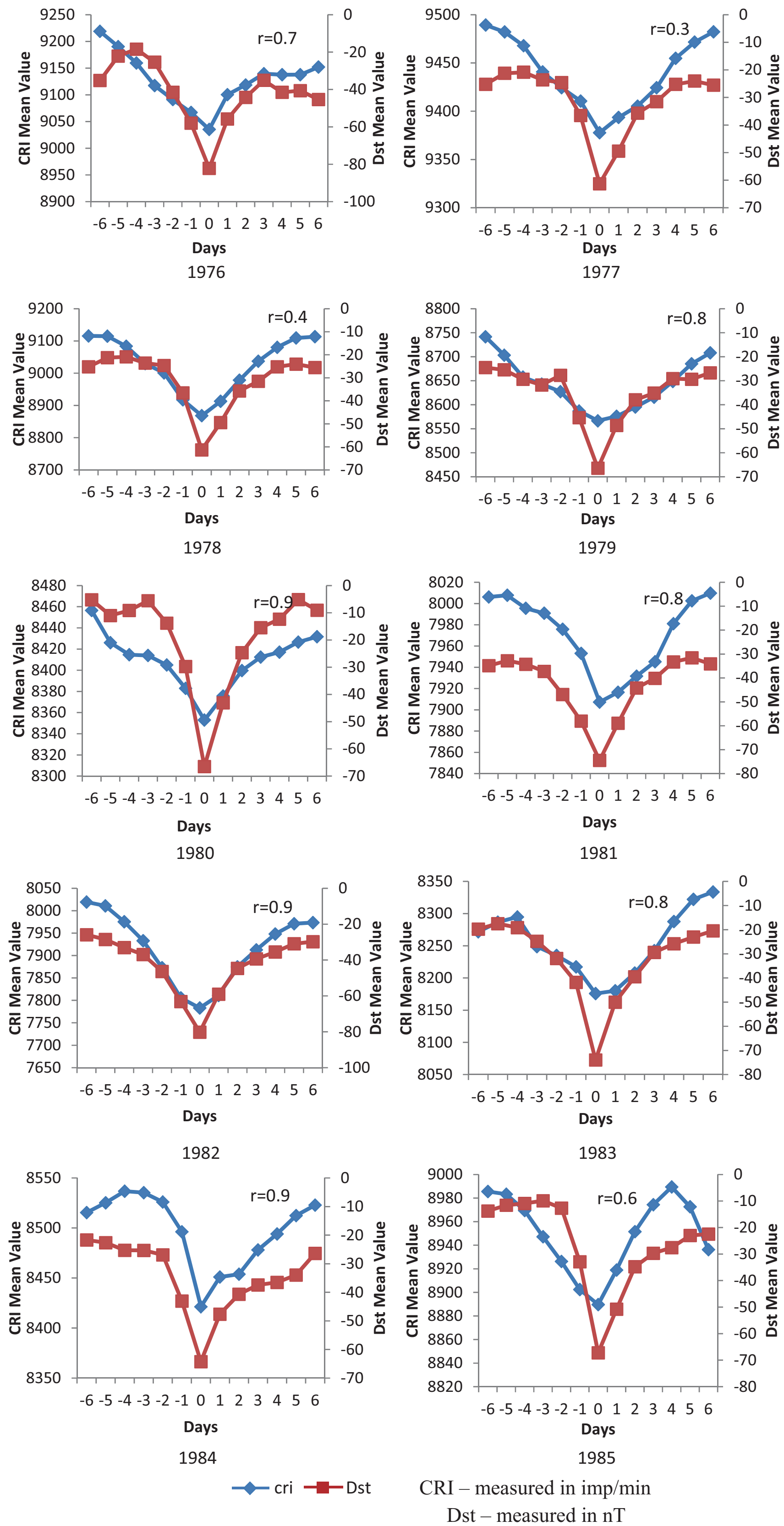


Figure 1. The result of Chree analysis from −6 day to +6 day with respect to the occurrence day of GS (zero epoch day). In order to study the pattern of CRI and Dst, the variation of their mean values is plotted for solar cycle 21.

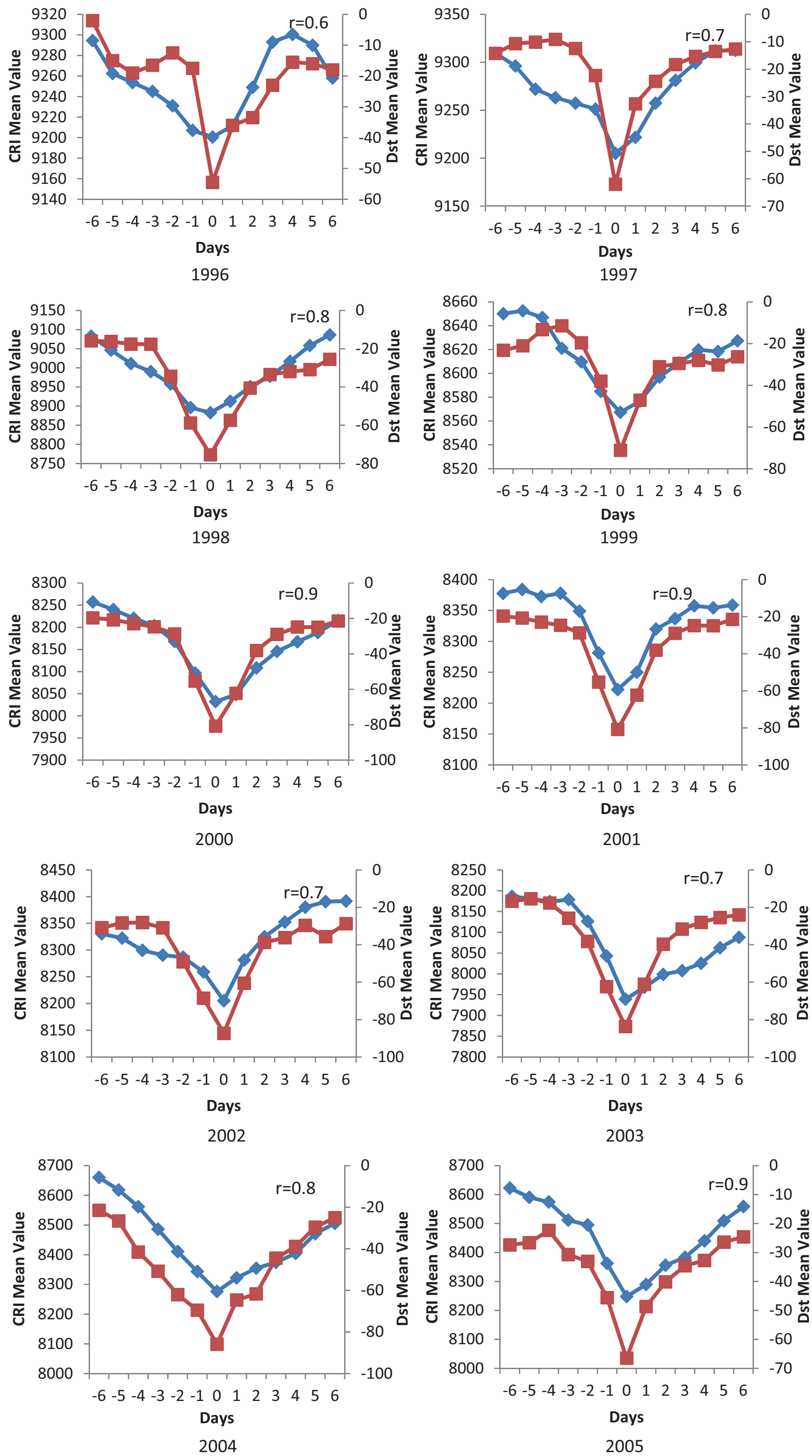


Figure 2. The result of Chree analysis from −6 day to +6 day with respect to the occurrence day of GS (zero epoch day). In order to study the pattern of CRI and Dst, the variation of their mean values is plotted for solar cycle 23.

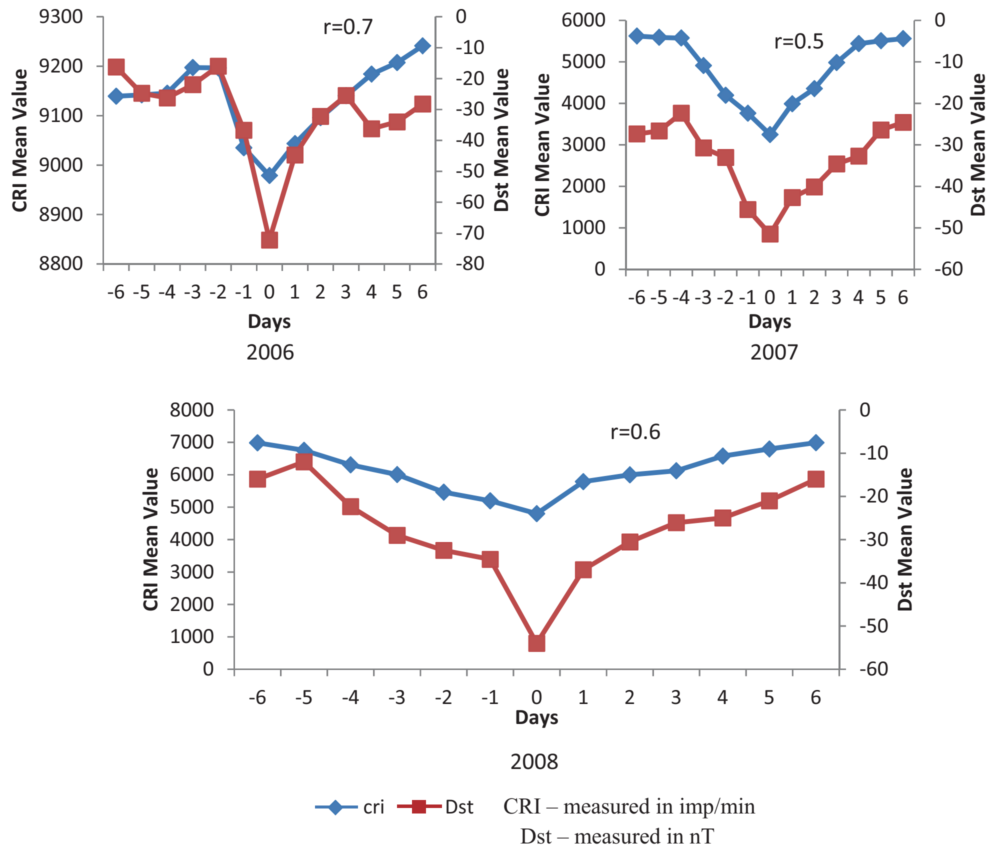


Figure 2. *Continued.*

that the depressions in CRI produced by co-rotating streams are smaller as compared to the flare-associated streams. Sabbah (2000) also studied the behavior of cosmic rays with high speed solar-wind events and found that the perturbations in the IMF produced due to high speed of the solar wind are responsible for the decrease in CRI. The study of CRI and its association with various parameters is important for understanding the phenomenon's occurs in the atmosphere.

2. Data analysis and method

For the study of cosmic ray, the pressure-corrected data (daily mean) has been taken from Moscow Neutron Monitor Station (http://cro.izmiran.rssi.ru/mosc/main.htm) while the data for solar wind speed, Bz and Dst, is obtained from the Omniweb data center (http://omniweb.gsfc.nasa.gov/cgi/nx1.cgi). The method which we have opted for the analysis is the superposed epoch method, also known as the Chree analysis. The occurrence day of geomagnetic storms is considered as the zero day (criteria Dst ≤ -50 nT). We used unbinned data for our study with the time resolution of one day. Now, by considering Dst ≤ -50 nT as the trigger day mean value, the limit of ± 6 values have been considered in the observation ($-1, -2, -3, -4, -5, -6$ values taken above the -50 nT and $+1, +2, +3, +4, +5, +6$ values taken below the -50 nT). Then we have found the average of all the observations in order to plot the graph. We have also calculated the average correlation coefficient of CRI with Dst, V, B, $|Bz|$ and $V \cdot |Bz|$ for both the solar cycles.

3. Results and discussion

3.1 *CRI and Dst*

Figures 1, 2 is based on revealing the union of Dst with CRI. For a comparative study, we have examined the patterns of Dst and CRI for both the consecutive odd solar cycles 21 and 23, and our examination arrived at an interesting result, i.e. the strongest decrement in CRI happens around the same time when Dst achieve their minima. Moreover, we have also found the correlation coefficient of Dst with CRI for solar cycle 23 (0.8) and solar cycle 21 (0.7), and it is observed to be high which

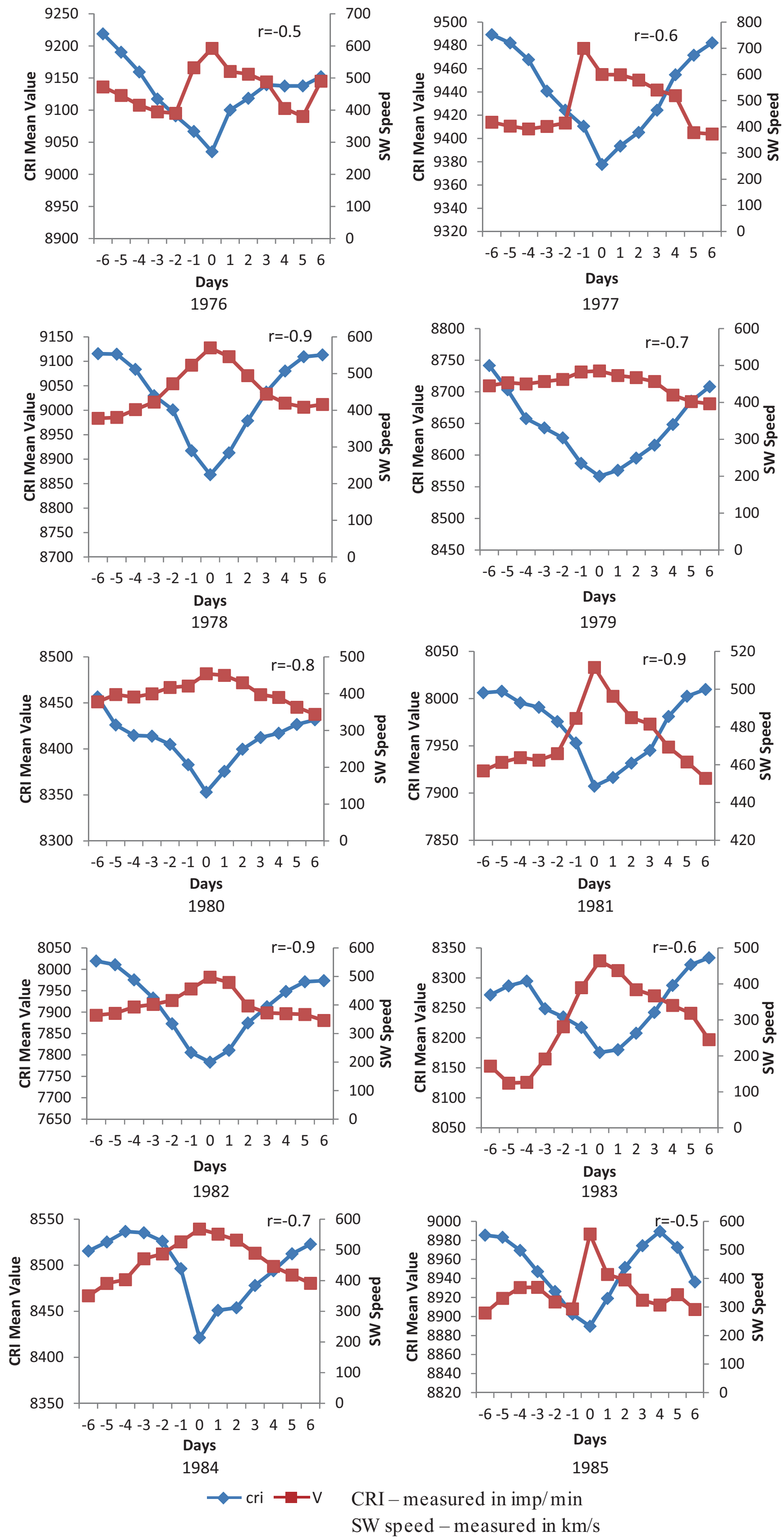


Figure 3. The result of Chree analysis from −6 day to +6 day with respect to the occurrence day of GS (zero epoch day). In order to study the pattern of CRI and SW speed, the variation of their mean values is plotted for solar cycle 21.

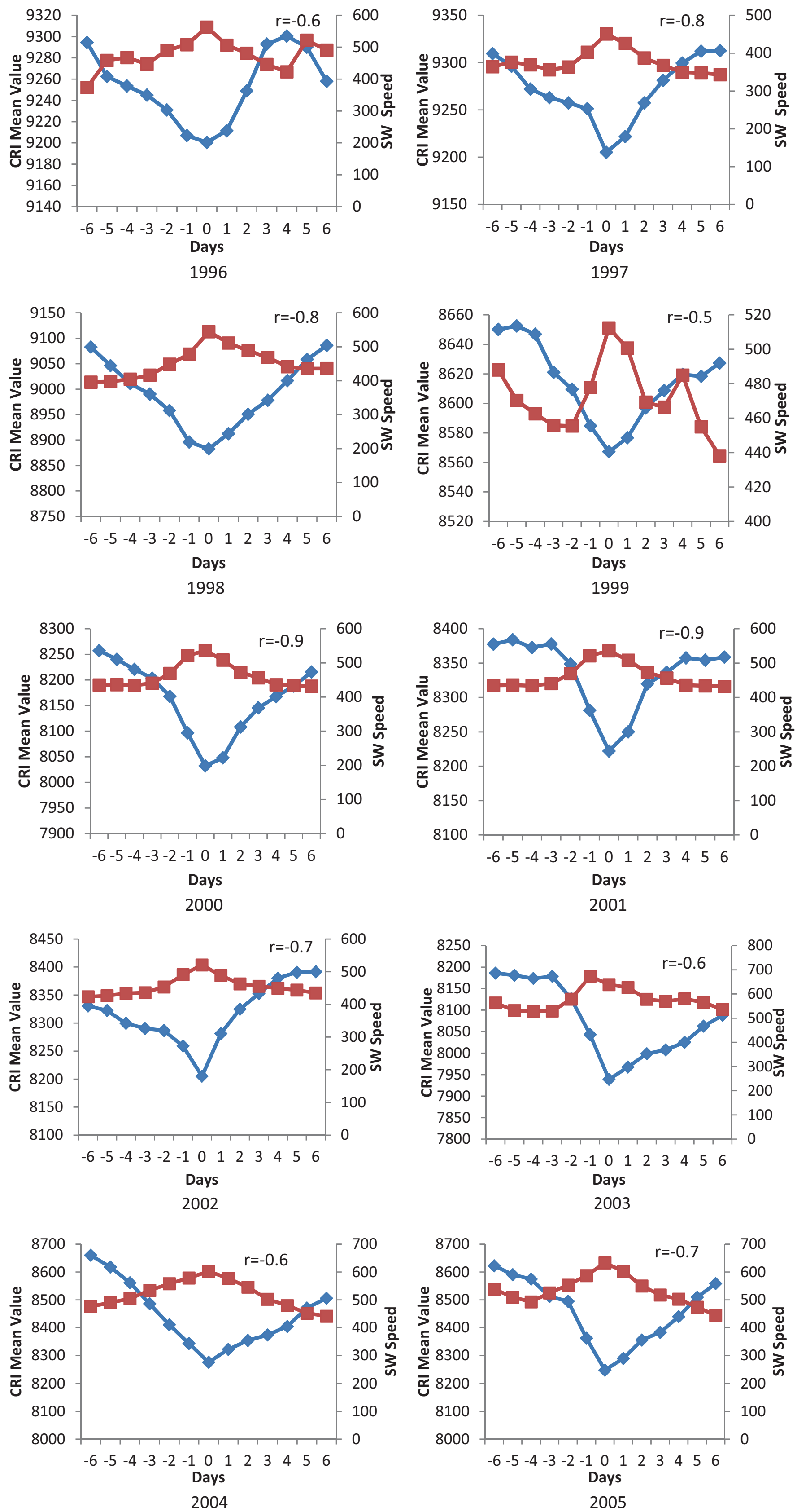


Figure 4. The result of Chree analysis from −6 day to +6 day with respect to the occurrence day of GS (zero epoch day). In order to study the pattern of CRI and SW speed, the variation of their mean values is plotted for solar cycle 23.

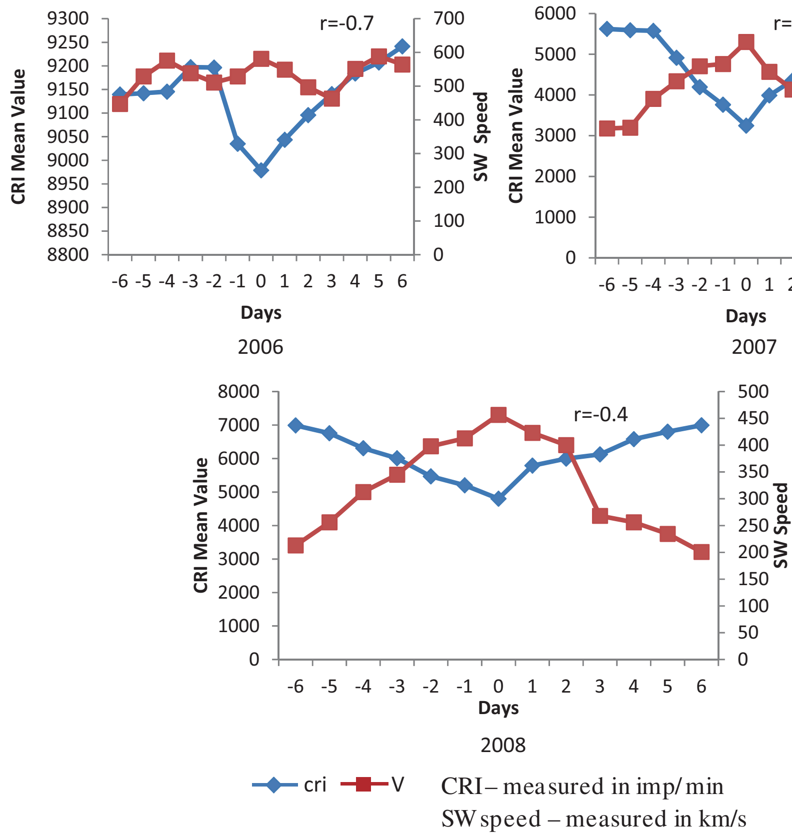


Figure 4. *Continued.*

obviously displays that both these parameters are highly correlated for both the solar cycles. Our outcomes are in great support of the disclosures of Mathpal *et al*. (2018) and Shrivastava *et al*. (2001).

3.2 *CRI and V*

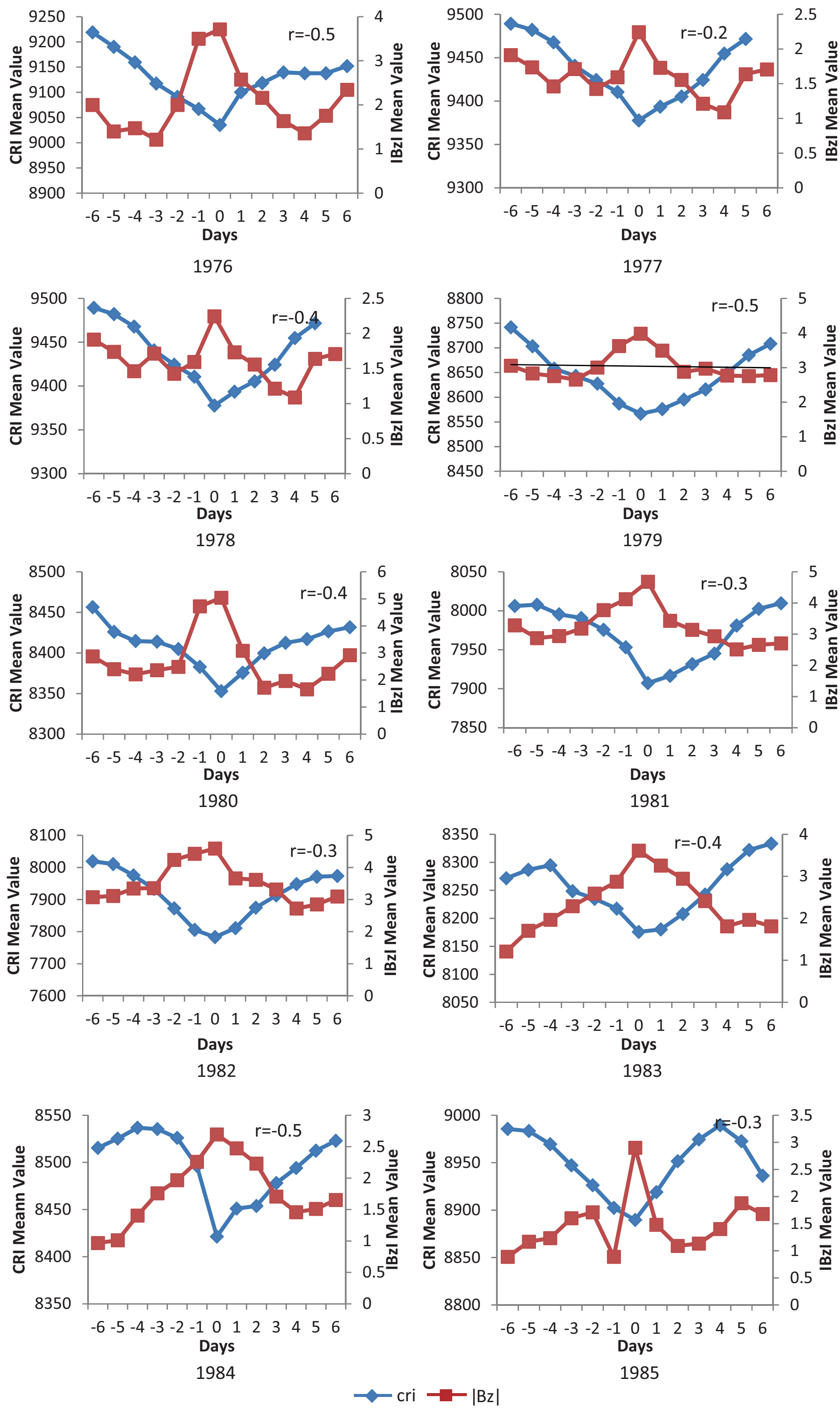
For the similar studied period, we additionally found the relation between CRI and V (Figures 3, 4). During our study for both the solar cycles, we examined that for most of the years, as CRI starts to decrease and achieve its minima on 0 day, at the same time V starts to increase and gains its maxima on zero day simultaneously, i.e. the pattern of CRI looks like an inverted carbon copy of the V pattern. It is imperative to specify here that an odd behavior is seen for 1977 in which we have observed a one-day time lag. We saw a similar kind of uncommon conduct of CRI with V in 2003 having a time lag of one day. The time lag can be the result of the high speed of the solar wind. This kind of strange conduct of solar wind is also observed by Kharayat and Prasad (2017). Even the correlation coefficient between CRI and V is sufficiently high to demonstrate that these parameters are well anti-correlated with each other (Table 1).

Table 1. Correlation coefficients between various parameters.

Parameters	Solar cycle 21	Solar cycle 23
CRI and Dst	0.7	0.8
CRI and $V \cdot \|Bz\|$	− 0.8	− 0.8
CRI and $\|Bz\|$	− 0.3	− 0.4
CRI and B	− 0.2	− 0.3
CRI and SW speed	− 0.6	− 0.7

3.3 *CRI vs.* $|Bz|$ *and CRI vs. B*

We have contrasted the profiles of CRI with $|Bz|$ and have come to the resolution that the strongest increment in $|Bz|$ happens on the same day when CRI reaches its minimum peak (on 0 day), i.e. as $|Bz|$ starts to increase, the CRI begins to diminish and achieve their minima when $|Bz|$ maximizes (Figures 5, 6). We likewise assessed the correlation coefficient between



$|Bz|$ – mesured in nT

CRI – measured in imp/min

Figure 5. The result of Chree analysis from −6 day to +6 day with respect to the occurrence day of GS (zero epoch day). In order to study the pattern of Bz and CRI, the variation of their mean values is plotted for solar cycle 21.

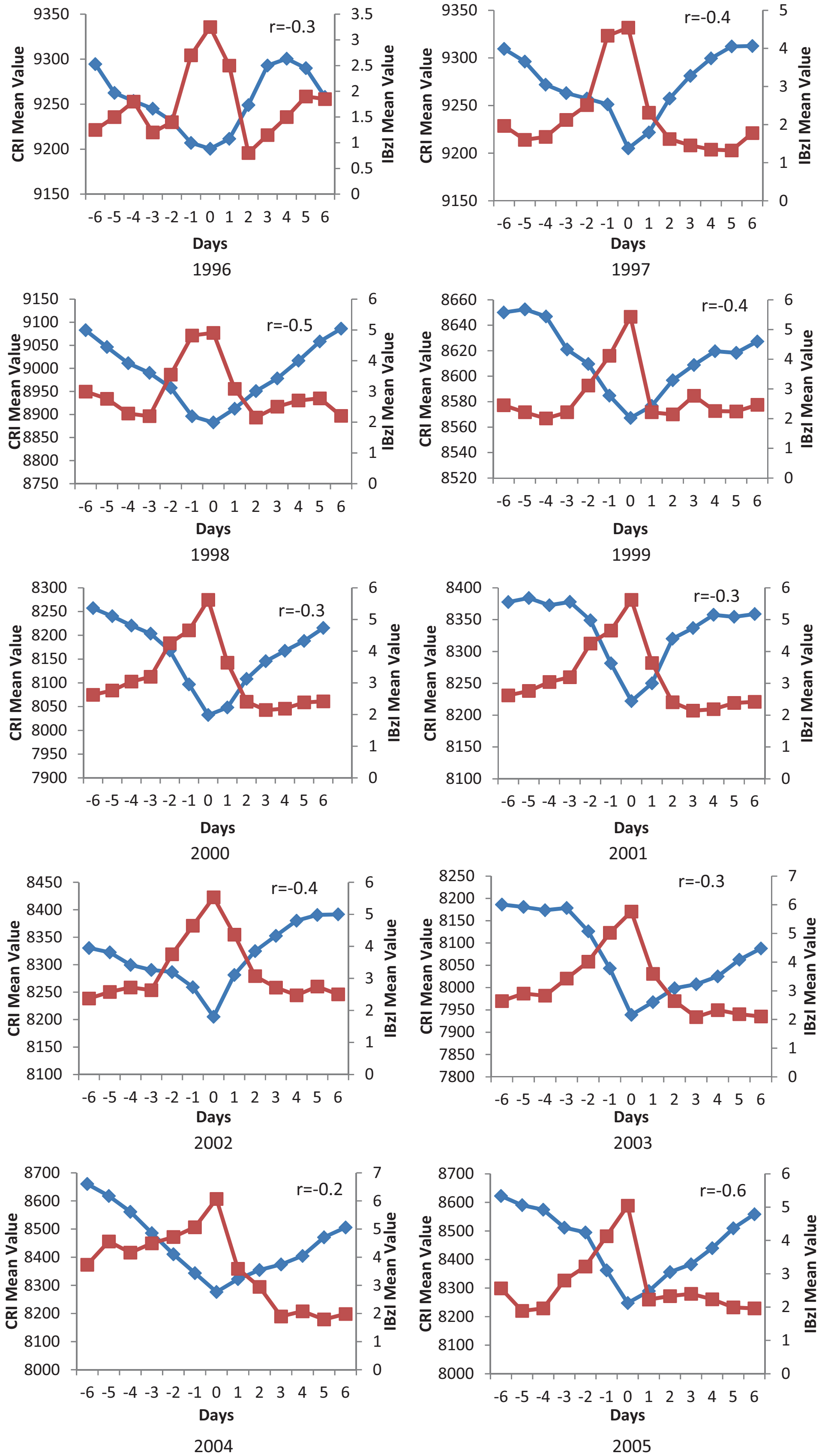


Figure 6. The result of Chree analysis from −6 day to +6 day with respect to the occurrence day of GS (zero epoch day). In order to study the pattern of $|Bz|$ and CRI, the variation of their mean values is plotted for solar cycle 23.

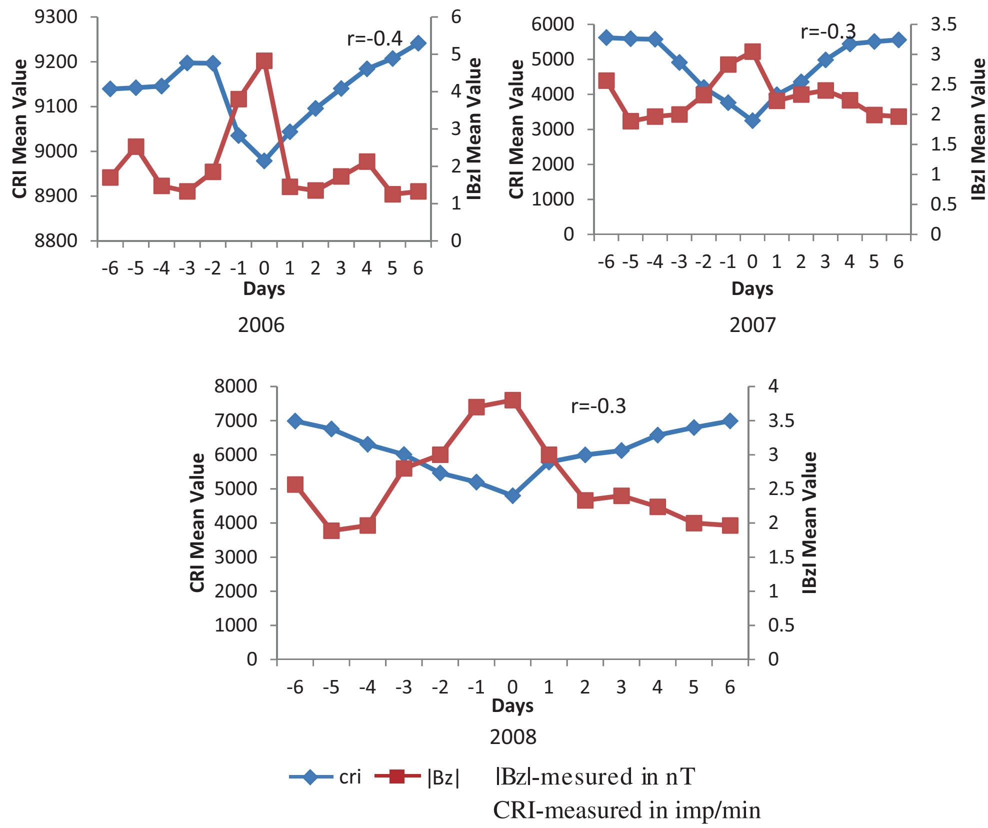


Figure 6. *Continued.*

CRI and $|Bz|$, and it is observed to be -0.3 for solar cycle 21 and -0.4 for solar cycle 23, which exhibit that CRI and $|Bz|$ are weakly associated with each other for both the solar cycles. Our findings support the earlier revelations of Duggal *et al.* (1983). We have also analysed the graphs of CRI vs. B and found that the patterns are almost similar as in the case of $|Bz|$ but the average correlation coefficient is found to be weak in comparison to CRI vs. $|Bz|$ (Table 1), which clearly indicates that in comparison to net IMF (B), the Bz component is more effective for the production of variations in the intensity of cosmic rays, which is in favor of earlier findings of Kane (2010).

3.4 *CRI vs.* $V \cdot |Bz|$

After investigating the association of CRI with V and $|Bz|$ separately, we have inspected Figures 7, 8, 9 and 10 to understand how CRI pattern changes with $V \cdot |Bz|$. We arrived at an extraordinarily fascinating conclusion that for both the solar cycles, CRI is highly anti-correlated with $V \cdot |Bz|$ when compared with V or $|Bz|$ alone and this is reconfirmed after calculating the correlation coefficient (-0.8) which is found to be high in comparison to CRI vs. V and CRI vs. $|Bz|$ for both the solar cycles (Table 1). Even the profile structures which show the association among Dst and $V \cdot |Bz|$ is similar for both the solar cycles which obviously demonstrates that the strongest decrement in CRI occurs on the same day when $V \cdot |Bz|$ achieves its strongest increment (i.e. on 0 day) with no time lag (Figures 7, 8, 9, 10). The product of V and $|Bz|$ reflects both convection with the solar wind and diffusion by the IMF. As per the theory of cosmic ray modulation given by Parker (1965), the association between $V \cdot |Bz|$ and the variation in intensity of cosmic rays has a reasonable physical origin; this is a hidden effect of the electric field in the cosmic ray transport. In general, V and Bz act together in the process of the convection–diffusion propagation of cosmic rays and is also responsible for recurrent changes in their intensity. Consequently, it is significant to calculate the correlation of $V \cdot |Bz|$ to study their role in the modulation process rather than V or $|Bz|$ independently.

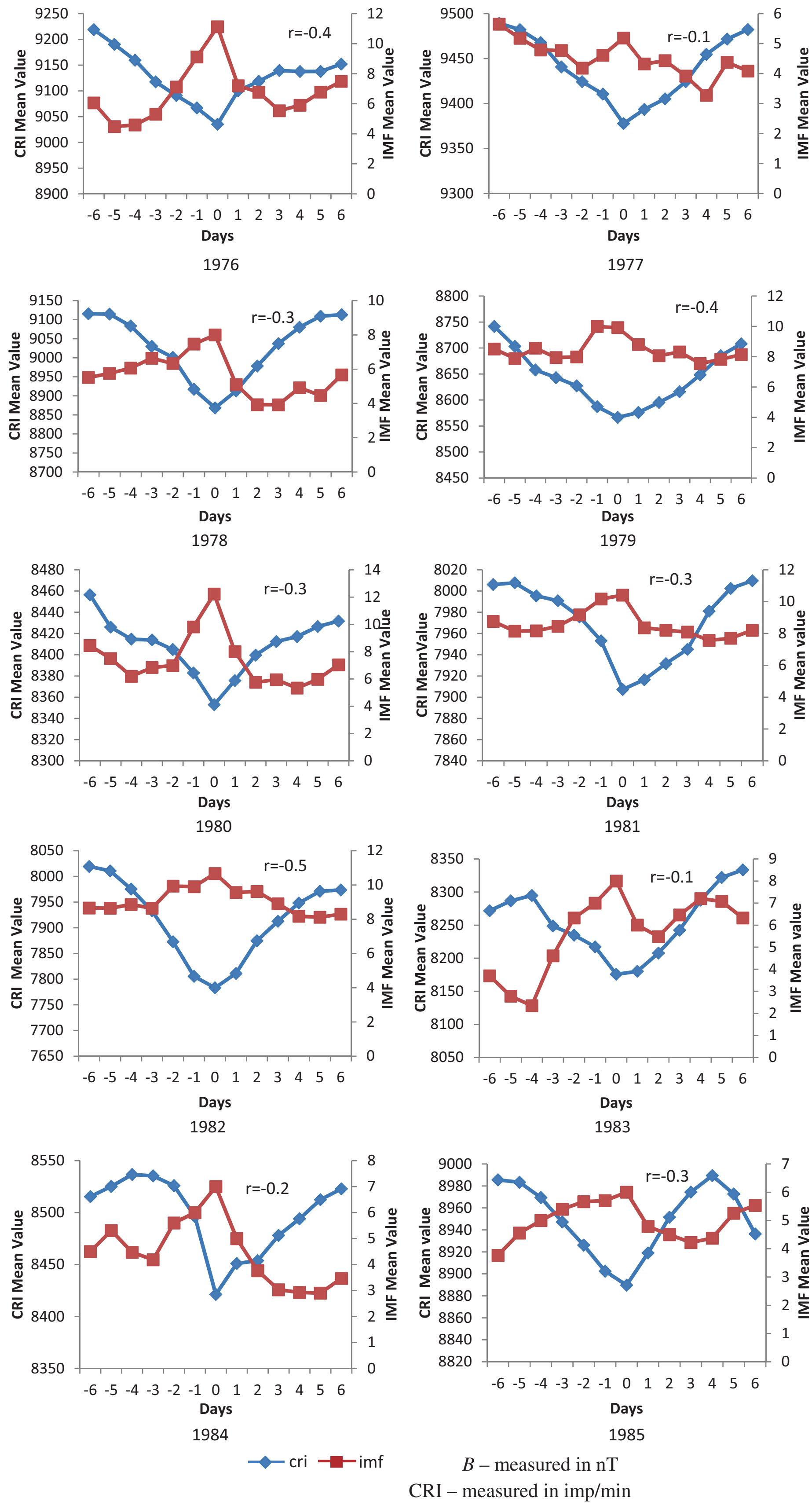


Figure 7. The result of Chree analysis from −6 day to +6 day with respect to the occurrence day of GS (zero epoch day). In order to study the pattern of IMF (B) and CRI, the variation of their mean values is plotted for solar cycle 21.

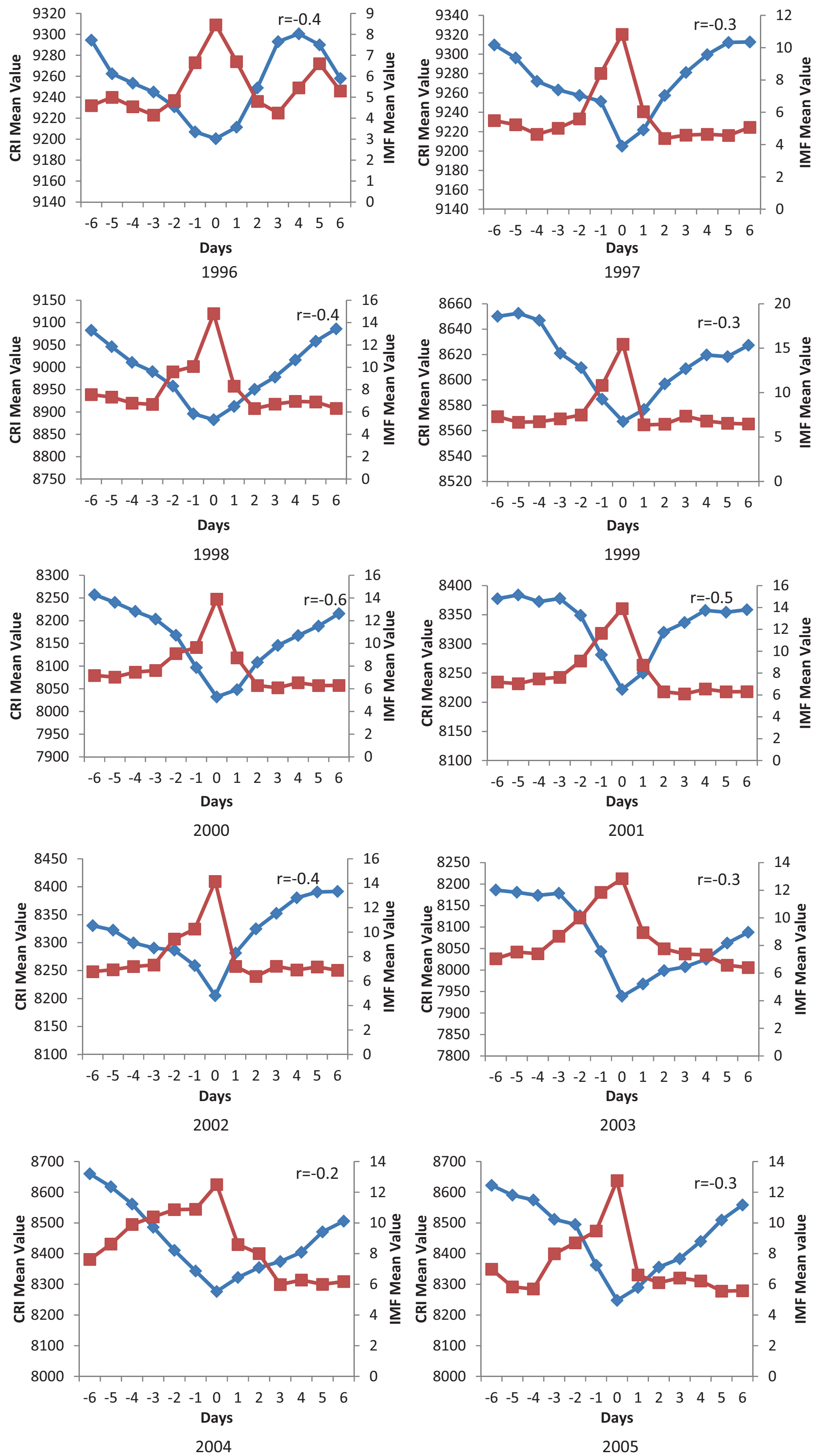


Figure 8. The result of Chree analysis from −6 day to +6 day with respect to the occurrence day of GS (zero epoch day). In order to study the pattern of IMF (B) and CRI, the variation of their mean values is plotted for solar cycle 23.

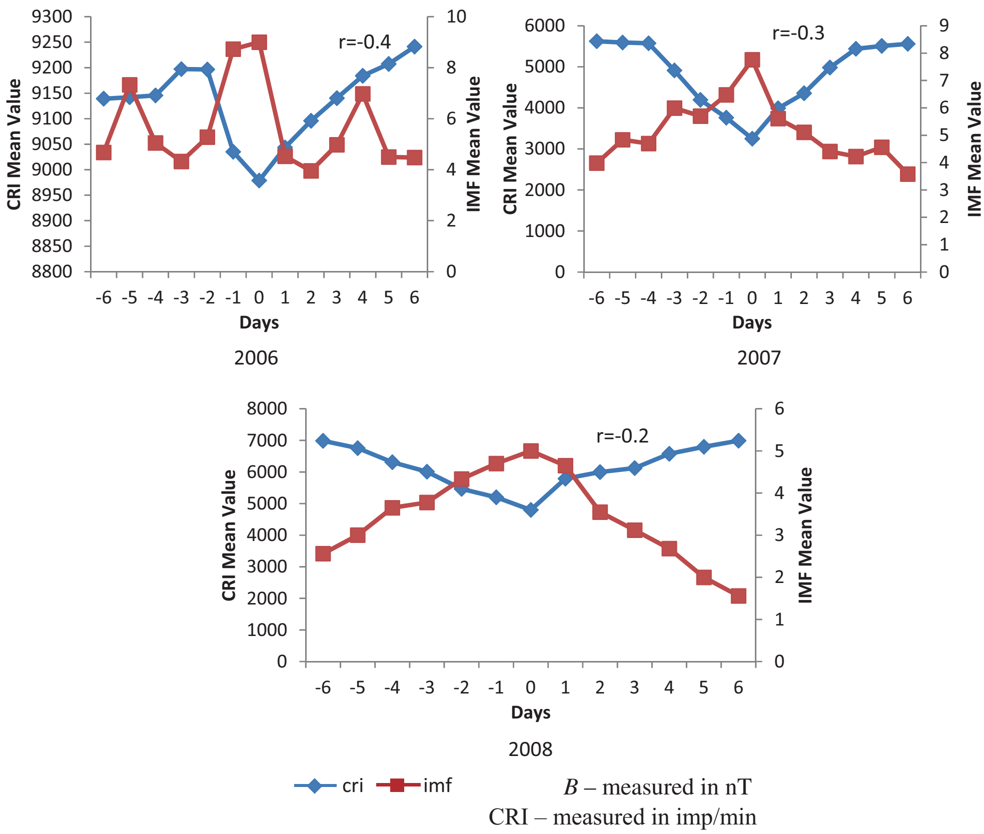


Figure 8. *Continued.*

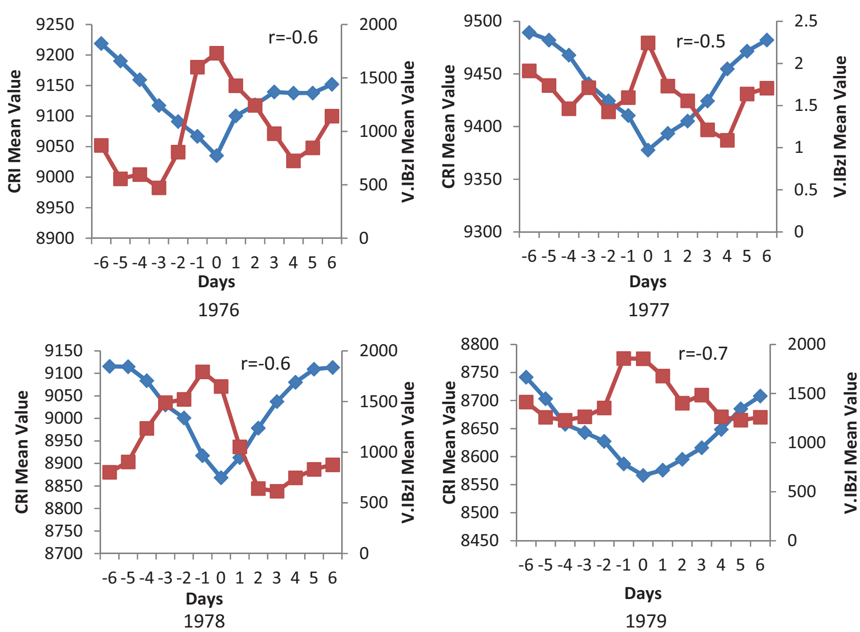


Figure 9. The result of Chree analysis from −6 day to +6 day with respect to the occurrence day of GS (zero epoch day). In order to study the pattern of $V \cdot |Bz|$ and CRI, the variation of their mean values is plotted for solar cycle 21.

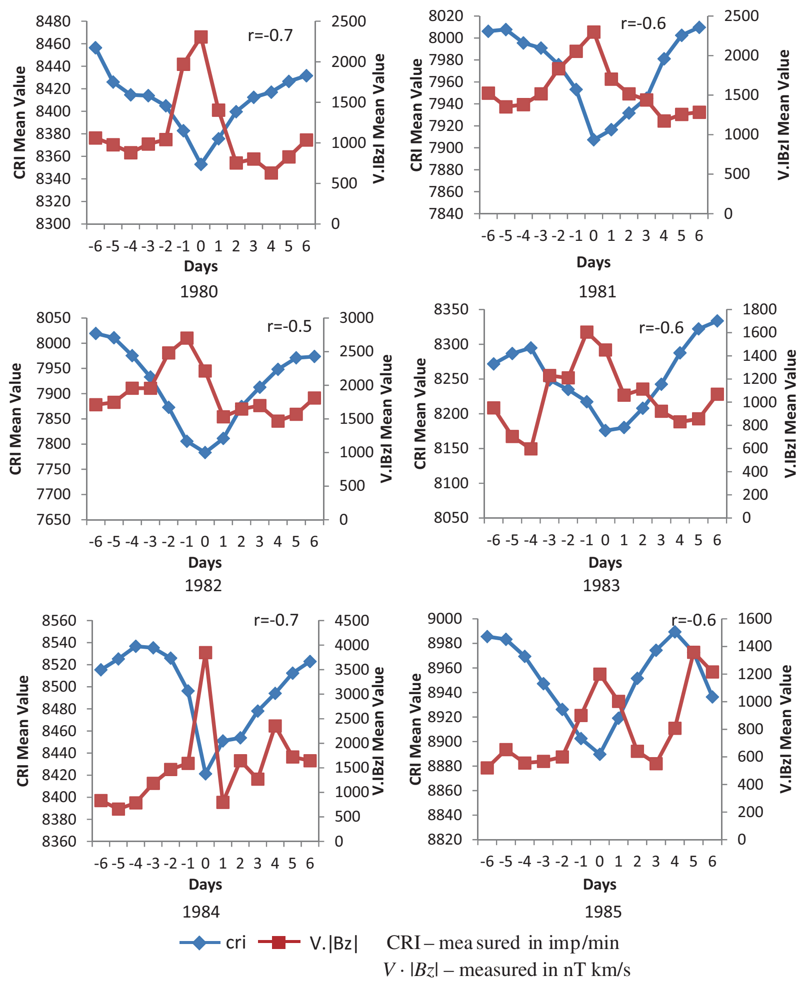


Figure 9. *Continued.*

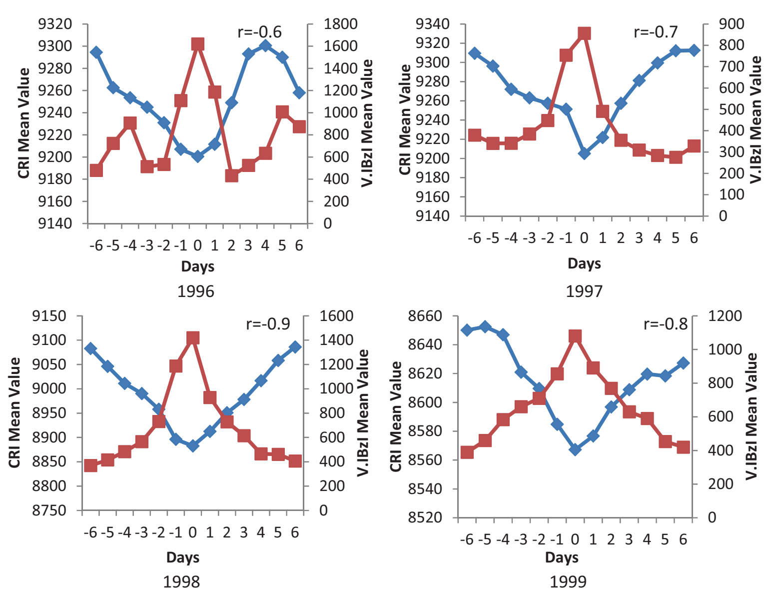


Figure 10. The result of Chree analysis from −6 day to +6 day with respect to the occurrence day of GS (zero epoch day). In order to study the pattern of $V \cdot |Bz|$ and CRI, the variation of their mean values is plotted for solar cycle 23.

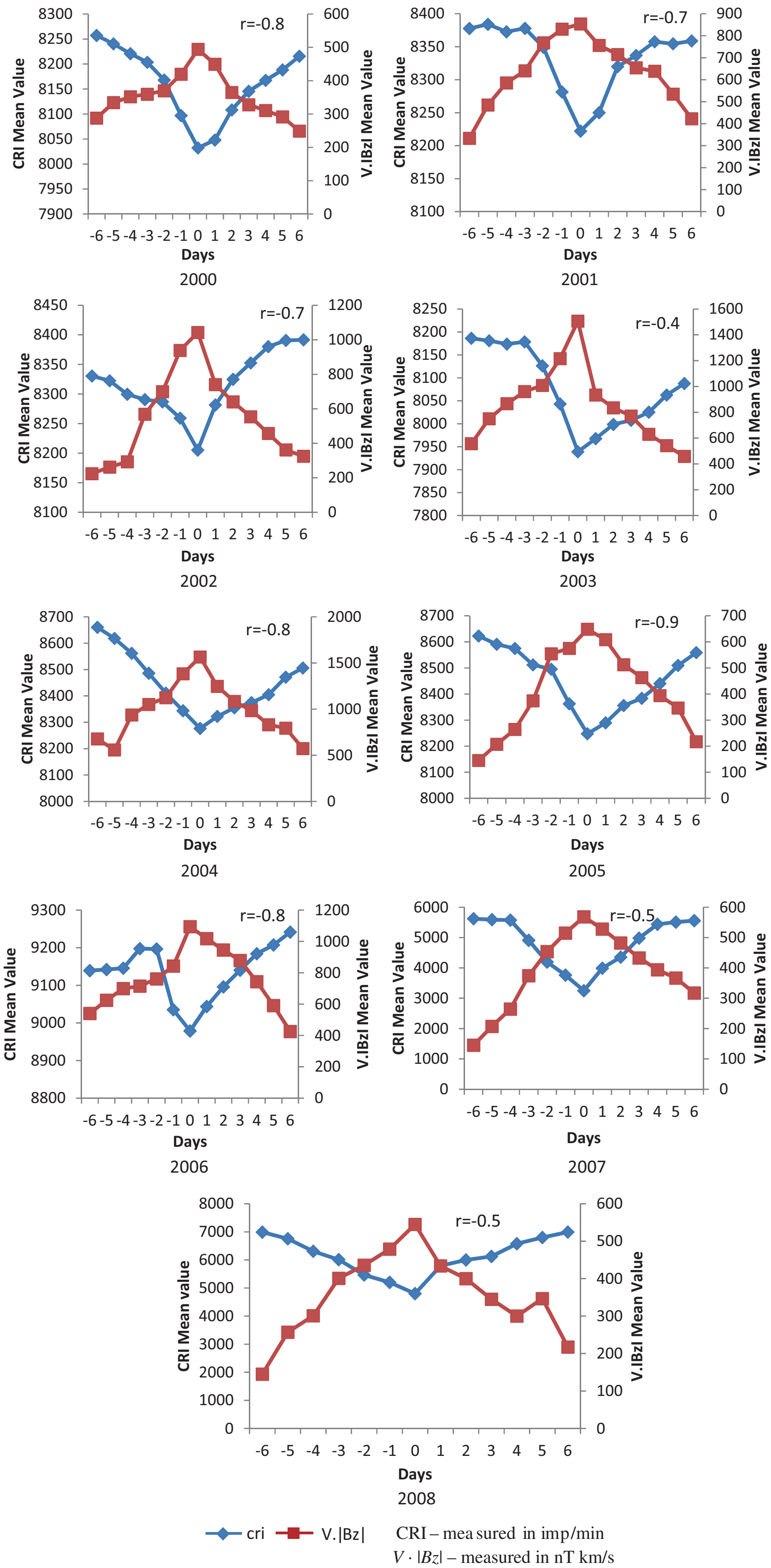


Figure 10. *Continued.*

4. Conclusions

- The strongest decrement in CRI happens around the same time when Dst achieve their minima.
- The correlation coefficient of Dst with CRI for solar cycle 23 (0.8) and solar cycle 21 (0.7) is observed high which obviously displays that both of these parameters are highly correlated for both the solar cycles.
- During the study of CRI vs. V, odd behavior is seen for 1977 and 2003 in which we have observed a one-day time lag. This time lag can be the result of high speed of the solar wind.
- The correlation coefficient between CRI and $|Bz|$ is observed to be -0.3 for solar cycle 21 and -0.4 for solar cycle 23, which is found to be high when compared with the correlation coefficient of CRI and IMF.
- CRI is highly anti-correlated with $V \cdot |Bz|$ when contrasted with V or $|Bz|$ alone.
- Correlation coefficient of CRI vs. $V \cdot |Bz|$ is found to be high (0.8) in comparison to CRI vs. V and CRI vs. $|Bz|$ for both the solar cycles.

Acknowledgements

The authors are thankful to IUCAA, Pune for content page service and are also thankful to ARIES, Nainital for providing library and computing facilities.

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