

Effects of Hysteresis Between Maximum CME Speed Index and Typical Solar Activity Indicators During Cycle 23

A. Özgüç · A. Kilcik · J.P. Rozelot

Received: 13 February 2012 / Accepted: 25 July 2012 / Published online: 14 August 2012
© Springer Science+Business Media B.V. 2012

Abstract Using the smoothed time series of maximum CME speed index for solar cycle 23, it is found that this index, analyzed jointly with six other solar activity indicators, shows a hysteresis phenomenon. The total solar irradiance, coronal index, solar radio flux (10.7 cm), Mg II core-to-wing ratio, sunspot area, and H α flare index follow different paths for the ascending and the descending phases of solar cycle 23, while a saturation effect exists at the maximum phase of the cycle. However, the separations between the paths are not the same for the different solar activity indicators used: the H α flare index and total solar irradiance depict broad loops, while the Mg II core-to-wing ratio and sunspot area depict narrow hysteresis loops. The lag times of these indices with respect to the maximum CME speed index are discussed, confirming that the hysteresis represents a clue in the search for physical processes responsible for changing solar emission.

1. Introduction

Studies of the relationship between different coronal activity indices during the solar cycle may provide evidence about the storage of energy in the corona. Donnelly (1991) has shown that some of these activity indicators such as the 10.7 cm solar radio flux, the Ca II K index, and the Ly α irradiance at 1216 Å follow different paths for the ascending and descending phases of the solar cycle, displaying a “hysteresis”-like phenomenon. In some cases, these observed hysteresis patterns are repeated over more than one solar cycle, indicating that this is a normal feature of solar activity. Considering seven indices of solar activity, Bachmann

A. Özgüç (✉)
Kandilli Observatory and E.R.I Bogazici University, Istanbul 34684, Turkey
e-mail: ozguc@boun.edu.tr

A. Kilcik
Big Bear Solar Observatory, Big Bear City, CA 92314, USA

J.P. Rozelot
Nice University, CNRS-UMR 7293, OCA Lagrange Dpt., Bvd de l’Observatoire, BP 4229,
06304 Nice Cedex 4, France

and White (1994) showed that smoothed time series of upper chromospheric activity exhibit hysteresis when compared to the international sunspot number. Specifically, the chromospheric indices were shown to lag behind the sunspot number by one month to several months, depending on the index. This was interpreted in terms of active regions evolving from the photosphere upward. Bachmann and White (1994) expressed their confidence in noticing that the hysteresis is thus a real phenomenon, not a result of instrumental effects, and they were able to estimate lag times of activity indices compared to the sunspot number. However, some of their measured delay times were significantly larger than the short-term delays associated with the rotational modulation of enhanced solar activity.

Özgüç and Ataç (2002) extended this analysis to include the variation of the $H\alpha$ flare index, as well as some of the coronal activity indices, over three solar cycles (20, 21, and 22). They found that the hysteresis effects are irregular over the three cycles. A lag between solar cycle indices and flare occurrence was also noted for hard X-ray flares observed during cycle 21 (Bai, 1993; Bromund, McTiernan, and Kane, 1995). Some other authors go further to show the hysteresis between the p -mode oscillation frequency and activity indicators; some evidence for this effect has been presented, for example, by Jimenez-Reyes *et al.* (1998). They analyzed the low-degree p -mode frequency shifts and solar activity indices (radio flux at 10.7 cm and magnetic index) over solar cycle 22, observing a hysteresis phenomenon. Moreno-Insertis and Solanki (2000) suggested that high latitude magnetic fields are necessary to produce a significant hysteresis difference between odd- and even-degree p -mode frequencies. The hysteresis effect has also been recognized as a common feature of cosmic ray modulation (Dorman *et al.*, 1999; Kane, 2011).

In this paper, we expand the preceding works to show that hysteresis occurs between the maximum coronal mass ejection speed index (MCMESI) and other solar activity indices during solar cycle 23. The total solar irradiance (TSI), $H\alpha$ flare index (FI), coronal index (CI), solar radio flux at 10.7 cm (F10.7), Mg II core-to-wing ratio (Mg II), and sunspot area (SSA) are chosen here as indicators of solar activity. Although the shape of hysteresis curves among several indices has been studied in the past (Bachmann and White, 1994), this is the first time that such relations are seen between this index (MCMESI) and other solar indices.

2. Solar Activity Indices

A cross-correlation analysis is made on the seven indices covering a period of time ranging from 1 January 1996 to 31 December 2006 (solar cycle 23). The solar activity indicators used in this study are briefly described as follows.

- i) The MCMESI data are derived from the Large Angle and Spectrometric Coronagraph (LASCO; Brueckner *et al.*, 1995) on the *Solar and Heliospheric Observatory* (SOHO) mission, as compiled in the CME catalog (Yashiro *et al.*, 2004; Gopalswamy *et al.*, 2009). The determination of the MCMESI is based on the measurements of highest daily linear CME speed averaged over one month (for more details, see Kilcik *et al.*, 2011a).
- ii) FI is evaluated as a measure of the short-lived activity on the Sun and is roughly proportional to the total energy emitted by a flare (Özgüç, Ataç, and Rybák 2003, 2004).
- iii) CI is derived by Rybansky *et al.* (1994) from measurements of the total energy emitted by the corona in the emission line of Fe XVI at a wavelength of 5303 Å. Lomnický Stit in the Slovak Republic served as the reference station for calculating this index.

- iv) F10.7 is derived from the daily measurements of the integrated radio emission originating from the high chromosphere and low corona at 2800 MHz (10.7 cm wavelength), which has been reported by the National Research Council (NRC) of Canada since 1947. The flux values are expressed in solar flux units ($1 \text{ s.f.u.} = 10^{-22} \text{ W m}^{-2} \text{ Hz}^{-1}$). The characteristics of the observations are reviewed by Covington (1969).
- v) SSA is observed, measured, and compiled by the Royal Greenwich Observatory and USAF/NOAA. It is taken from the web page of the Marshall Space Flight Center. The FI, CI, and F10.7 data are taken from the National Geophysical Data Center (NGDC).¹
- vi) The Mg II index was first proposed by Heath and Schlesinger (1986). According to Cebula and DeLand (1998), the Mg II index is defined as the ratio between the core emission and the solar continuum intensity in the wings. This index is a dimensionless quantity measuring mid-UV solar activity. We used the NOAA Mg II daily index version 9.1 prepared by NOAA, Space Environment Center.²
- vii) TSI, a composite record of the Sun's total irradiance, is compiled from measurements made by five independent space-based radiometers since 1978. We used version 41 of that data set, which can be found at the webpage of PMODWRC.³

3. Analysis

We perform the 365-day running means using only common days of data to produce smoother hysteresis patterns and to suppress contributions from transients for cycle 23. The time variations of the studied activity indices are shown in two separate figures (Figures 1a and 1b). Figure 1a shows chromospheric and global indices, while Figure 1b represents the coronal indices. The following features may be noted (some of these are already known).

- i) Figure 1a shows a clear example of hysteresis between MCMESI and four indices, FI, Mg II, SSA, and TSI during cycle 23. An obvious delay in MCMESI is visible with respect to these four indices during the declining phase; clearly, MCMESI attains its peak later than the other indices.
- ii) As the ascending phase proceeds, these four indices increase almost simultaneously; likewise, during the descending phase they decline almost in parallel, except for MCMESI.
- iii) These four indices show very sharp double-peak maxima while MCMESI shows broad, double-humped structures, long enough to be seen even in 365-day moving averages.
- iv) The relative strengths of the two humps are different for different activity indices.
- v) Figure 1b shows also a clear example of hysteresis between MCMESI and two other indices, F10.7 and CI. Contrary to the other four indices, these two indices show hysteresis during the ascending phase of the cycle as well as during the descending one.

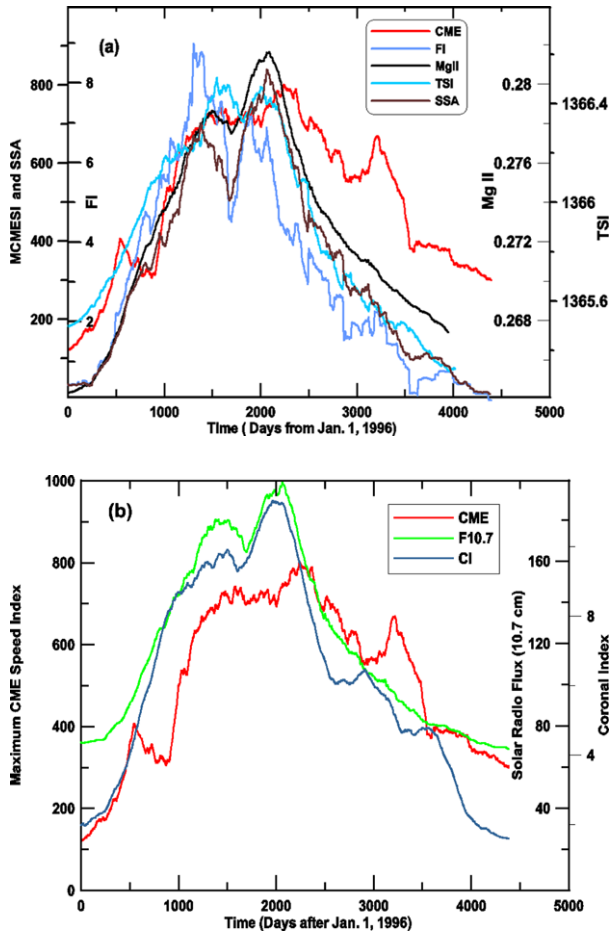
MCMESI was chosen to be the abscissa of all plots with identical scale in Figure 2 in order to display more clearly the effects of hysteresis. To avoid unnecessary details, we used the yearly means instead of the 365-day running means for drawing these plots. The plotted curves in Figure 2 clearly exhibit hysteresis. MCMESI does not follow the same path in the ascending and the descending parts of the solar cycles when it is plotted versus the

¹ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA.

²<http://www.swpc.noaa.gov/ftpd/ir/sbu/>.

³<ftp://ftp.pmodwrc.ch/pub/data/irradiance/composite/DataPlots/>.

Figure 1 (a) Time evolution of smoothed FI, Mg II, TSI, SSA, and MCMESI. Each plot is drawn with 365-day running means. The SSA values are divided by 2.5 to adjust to the MCMESI axis. (b) Time evolution of smoothed CI, F10.7, and MCMESI. Each plot is drawn with 365-day running means.



other activity indices. Arrows indicate the direction of time. The most interesting finding in Figure 2 is the separation (*i.e.*, the width of the hysteresis) between the two branches; these separations are not equal for different indices. The hysteresis pattern is almost the same for all the indicators, but with some difference in the widths: FI and TSI depict broad loops, while Mg II and SSA depict narrow hysteresis loops. The hysteresis cycles shown in Figure 2 exhibit clockwise circulation, *e.g.*, the descending path follows a lower track than for the ascending one, which is not a normal characteristic of hysteresis in magnetic materials. The saturation effects are seen at the maximum phases. Among the indices studied here, we find that the hysteresis effects are regarded approximately as simple phase shifts, and we quantify these phase shifts in terms of lag times behind the leading index, MCMESI.

A cross-correlation analysis has been applied to the studied parameters in order to find the delay times. The cross-correlation function is derived up to a time lag of ± 20 months, with a step of one month. The calculated cross-correlation coefficients between the indicators F10.7, Mg II, TSI, FI, CI, SSA, and MCMESI are shown in Figure 3, and the correlation coefficients for the most probable time lags and their statistical errors at a 95 % significance level are presented in Table 1. Although high correlation values are found between MCMESI

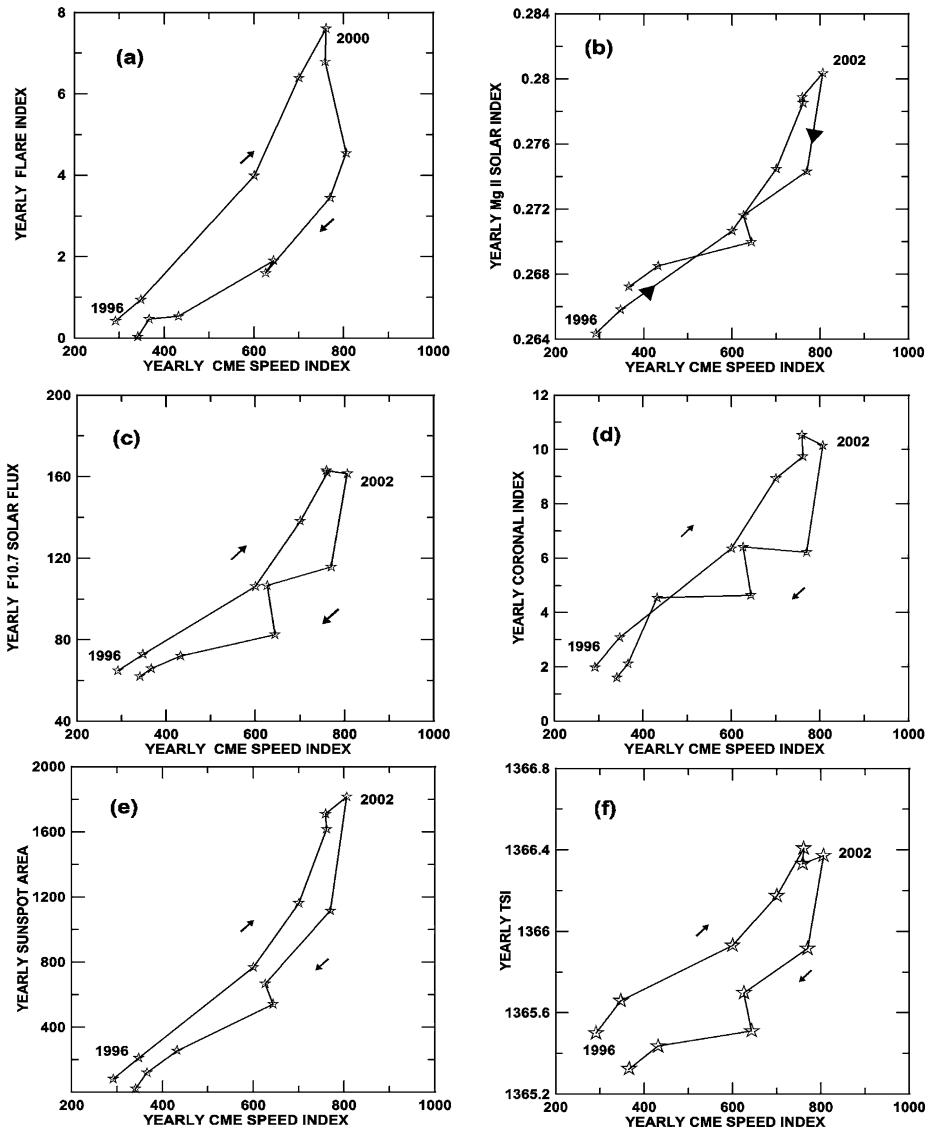


Figure 2 Scatter plots showing the hysteresis phenomenon for MCMESI versus (a) FI, (b) Mg II, (c) F10.7, (d) CI, (e) SSA, and (f) TSI. Arrows indicate the direction of time.

and Mg II ($r = 0.77$), F10.7 ($r = 0.74$), CI ($r = 0.72$), SSA ($r = 0.80$), FI ($r = 0.63$), and TSI ($r = 0.61$), four indices, Mg II, F10.7, SSA, and FI, show sharp peaks at zero lag, while CI and TSI show broad peaks centered around two (CI) and six (TSI) months. Such lag times can be seen clearly from the time profiles of the indices drawn in Figures 1a and 1b. The maximum time lag of the solar parameters with respect to the MCMESI seems to be six months for the solar cycle 23, seen between TSI and MCMESI.

Figure 3 Cross-correlations and time lags (in months) between MCMESI and the other six solar activity indices.

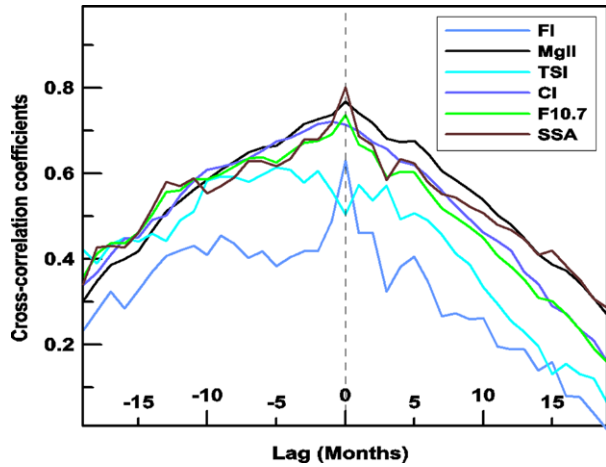


Table 1 Time lag (months) and correlation coefficient between MCMESI and six activity indices for solar cycle 23.

Activity index	Lag time (month)	Correlation coefficient
Flare index	0	0.63 ± 0.11
Sunspot area	0	0.80 ± 0.08
Solar radio flux	0	0.74 ± 0.09
Coronal index	2	0.72 ± 0.09
Total solar irradiance	6	0.61 ± 0.12
Mg II	0	0.77 ± 0.08

4. Discussion and Conclusion

The variation of MCMESI has been studied here compared to the behavior of six other solar activity indices to render as clearly as possible the hysteresis effect evolving along solar cycle 23. However, strong fluctuations of the solar activity with a time scale of the order of the characteristic lifetime of the largest active regions preclude a precise determination of the shape and lag times of the hysteresis effect. During the past three solar cycles, irradiance at all wavelengths has been monitored and its variability has been compared with traditional indices such as the sunspot number (SSN) and F10.7, increasing the number of possible cross-correlations. Some works suggest that certain pairs of indices exhibit hysteresis, such as odd- and even-degree *p*-mode frequencies and solar-cycle-dependent differences in their relative variations (Donnelly, 1991; Harvey, 1992; Moreno-Insertis and Solanki, 2000). Bachmann and White (1994) reported that the dynamics of active region evolution contributes to hysteresis effects between sunspot numbers and chromospheric activity indices. They also pointed out that this hysteresis can be expressed approximately as a hierarchy of delay times behind the leading index, the sunspot number. In our analysis, the figures show clearly that MCMESI always peaks after the other six indices studied.

Özgüç and Ataç (2002) showed that the choice of an activity indicator paired with another one may strongly influence the resulting hysteresis in a given cycle. They reported that, for cycle 21, all the indices they used (CI, SSA, and mean magnetic field (MMF)) show a hysteresis when they are plotted against FI. However, for cycle 22, they could not observe a

hysteresis on SSA versus FI. Although they observed a hysteresis between FI, CI, and MMF, the time direction was opposite when they were compared with cycle 21 (e.g., ascending branches follow higher tracks than descending ones).

Observationally, it appears that the p -mode frequency shifts and activity indices exhibit hysteresis. This effect was shown by some authors investigating only cycle 22 (Jimenez-Reyes *et al.*, 1998; Moreno-Insertis and Solanki, 2000; Tripathy *et al.*, 2001). Jimenez-Reyes *et al.* (1998) showed that a hysteresis exists between frequency shifts of odd- and even-degree p -modes themselves and also with two activity indices (F10.7 and MMF), for cycle 22. Comparing the shapes of the hysteresis found, they suggested that the hysteresis shape could also be due to time-delayed responses to a single phenomenon which can be located deeper in the Sun. Moreno-Insertis and Solanki (2000) reported that a hysteresis also exists between low-degree p -mode frequencies and magnetic flux. They suggested that if a given activity indicator basically depends on the magnetic flux distribution at a range of latitudes only, then a hysteresis can also appear between the frequency shift of one mode and that activity indicator. Tripathy *et al.* (2001) reported that the intermediate-degree p -mode frequencies of solar cycle 22 show a hysteresis phenomenon with respect to the magnetic indices, whereas no such effect exists for the radiative indices. By assuming that flares derive their energy from a coronal source and that flaring is the dominant mechanism for depleting that source, Wheatland and Litvinenko (2001) were able to argue that the global coronal response time is about nine months. The model they constructed was able to predict that both the flaring rate and the total free energy should lag behind the driving system, due to the coronal response time (their detailed model gives a lag time of ≈ 11 months). This effect may account for hysteresis phenomena between certain solar activity indices. They also reported that the analysis of time series of monthly sunspot numbers and monthly numbers of soft X-ray flares over the years 1976–1999 indicates a tendency for flare numbers to lag behind sunspot numbers by ≈ 6 months.

Very recently Sual, Prasad, and Singh (2012) studied solar wind velocity by using the permutation entropy to detect the hysteresis in a dynamical system. They found that the value of the permutation entropy follows different paths in the ascending and descending phases of solar cycle 23. They noted that while the ascent is fluctuating, the descent is smoother. Finally, Kilcik *et al.* (2011a), analyzing MCMESI, found that this indicator seems to better reflect the geomagnetic activity than other solar activity indicators such as SSN ($r = 0.76$), SSA, or FI. Comparing MCMESI with both the number of observed CMEs and geomagnetic indices (A_p and Dst), they found that the number of CMEs shows a few months' lag with respect to MCMESI while the geomagnetic indices do not (see Figure 4 in their paper). On the other hand, Kilcik *et al.* (2011b) compared MCMESI to the number of large (complex) and small (simple) sunspot groups and found that the large groups show better agreement with this index than the small ones, during solar cycle 23. Gopalswamy *et al.* (2009) and Ramesh (2010) reported that the CME occurrence rate similarly lags behind the sunspot maximum. From these comparisons, one can speculate that MCMESI is a powerful indicator for solar activity. A better understanding of this new indicator may exploit more meaningful physical links between solar activity and its geoeffectiveness.

To conclude, the hysteresis is due to the fact that the magnetic fields at different scales make different contributions to the total magnetic flux in diverse phases of the cycle. In the ascending branch, the curve of MCMESI and FI, Mg II, and TSI are similar. In the declining phase, MCMESI decreases much more slowly than FI, Mg II, and TSI and hence results in a hysteresis. Note that the delay of MCMESI in the declining phase increases gradually. Since the solar cycles represent complicated nonlinear dynamical phenomena, predicting the shape and the importance of the hysteresis effect is still elusive despite the large amount

of observational manifestations. As we discussed above, MCMESI is a good indicator of relevant solar-terrestrial phenomena. If this hypothesis is true, MCMESI time series could be regarded as a proxy data set to account for peculiar solar-induced effects in the heliosphere. Our results show that the hysteresis warrants serious considerations as a possible long-term feature of solar activity. Finally, we argue that this phenomenon represents a real delay both in the onset phase and in the decline phase of the solar activity; thus it could be an important clue in the search for physical processes responsible for changing solar emission at various wavelengths.

References

- Bachmann, K.T., White, O.R.: 1994, *Solar Phys.* **150**, 347.
- Bai, T.: 1993, *Astrophys. J.* **404**, 805.
- Bromund, K.R., McTiernan, J.M., Kane, S.R.: 1995, *Astrophys. J.* **455**, 733.
- Brueckner, G.E., Howard, R.A., Koomen, M.J., Korendyke, C.M., Michels, D.J., Moses, J.D., et al.: 1995, *Solar Phys.* **162**, 357.
- Cebula, R.P., DeLand, M.T.: 1998, *Solar Phys.* **177**, 117.
- Covington, E.A.: 1969, *J. Roy. Astron. Soc. Can.* **63**, 125.
- Donnelly, R.F.: 1991, *J. Geomagn. Geoelectr. Suppl.* **43**, 835.
- Dorman, L.I., Villaresi, G., Dorman, I.V., Iucci, N., Parisi, M.: 1999, In: Habbal, S.R., Halas, C.D. (eds.) *The Solar Wind Nine Conference, AIP Conf. Proc.* **471**, 621.
- Gopalswamy, N., Yashiro, S., Michalek, G., Stenborg, G., Vourlidas, A., Freeland, S., Howard, R.: 2009, *Earth Moon Planets* **104**, 295.
- Harvey, K.: 1992, In: Donnelly, R.F. (ed.) *Workshop on the Solar Electromagnetic Radiation Study for Solar Cycle 22*, NOAA, Boulder, 113.
- Heath, D., Schlesinger, B.M.: 1986, *J. Geophys. Res.* **91**, 8672.
- Jimenez-Reyes, S.J., Regulo, C., Palle, P.L., Roca Cortes, T.: 1998, *Astron. Astrophys.* **329**, 1119.
- Kane, R.P.: 2011, *Solar Phys.* **269**, 451.
- Kilcik, A., Yurchyshyn, V.B., Abramenko, V., Goode, P.R., Gopalswamy, N., Özgüç, A., Rozelot, J.P.: 2011a, *Astrophys. J.* **727**, 44.
- Kilcik, A., Yurchyshyn, V.B., Abramenko, V., Goode, P.R., Özgüç, A., Rozelot, J.P., Cao, W.: 2011b, *Astrophys. J.* **731**, 30.
- Moreno-Insertis, F., Solanki, S.K.: 2000, *Mon. Not. Roy. Astron. Soc.* **313**, 411.
- Özgüç, A., Ataç, T.: 2002, In: Wang, H.N., Xu, R. (eds.) *Solar-Terrestrial Magnetic Activity and Space Environment, COSPAR Colloq. Ser.* **14**, 447.
- Özgüç, A., Ataç, T., Rybák, J.: 2003, *Solar Phys.* **214**, 375.
- Özgüç, A., Ataç, T., Rybák, J.: 2004, *Solar Phys.* **223**, 287.
- Ramesh, K.B.: 2010, *Astrophys. J. Lett.* **712**, L77.
- Rybansky, M., Rusin, V., Gaspar, P., Altrrock, C.R.: 1994, *Solar Phys.* **152**, 487.
- Suyal, V., Prasad, A., Singh, H.P.: 2012, *Solar Phys.* **276**, 407.
- Tripathy, S.C., Kumar, B., Jain, K., Bhatnagar, A.: 2001, *Solar Phys.* **200**, 3.
- Wheatland, M.S., Litvinenko, Y.E.: 2001, *Astrophys. J.* **557**, 332.
- Yashiro, S., Gopalswamy, N., Michalek, G., St. Cyr, O.C., Plunkett, S.P., Rich, N.B., Howard, R.A.: 2004, *J. Geophys. Res.* **109**, A07105.