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# Long-term hemispheric variation of the flare index *

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**Abstract** The long-term hemispheric variation of the flare index is investigated. It is found that, (1) the phase difference of the flare index between the northern and southern hemispheres is about 6–7 months, which is near the time delay between flare activity and sunspot activity; (2) both the dominant and phase-leading hemisphere of the flare index is the northern hemisphere in the considered time interval, implying that the hemispheric asynchrony of solar activity has a close connection with the N-S asymmetry of solar activity.

**Key words:** Sun: activity — Sun: flares — methods: data analysis

## 1 INTRODUCTION

The activity of the Sun has been studied in several ways for a long time; its complex temporal and spatial behavior has been widely scrutinized. Solar-activity indices vary over the solar disk, and various activity indices cannot be considered to be symmetrical between the solar northern and southern hemispheres. The asymmetrical distribution of solar activity represents an important detail in solar dynamics, which is related to research about the genesis of the solar cycle and related activity. The N-S asymmetries of different solar activities, such as sunspot numbers, sunspot group numbers, sunspot areas, numbers of flares, the flare index, filaments, radio bursts, coronal holes, coronal mass ejections, photospheric magnetic fields, faculae, and green corona intensity, have been extensively studied by various authors (Oliver & Ballester 1994; Ataç & Özgüç 1996; Verma 1987; Gao et al. 2007, 2009; Li et al. 2002, 2003; Zhang et al. 2007; Yan et al. 2008; Cho & Chang 2011; Deng et al. 2011a, 2012; Xie et al. 2012). These studies have indicated that the N-S asymmetry of solar activities is a real phenomenon and is not due to random fluctuations (for details, see Vizoso & Ballester 1990; Li et al. 2002; Carbonell et al. 2007).

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Generally, solar activities in the northern and southern hemispheres are highly synchronous, forming the famous “butterfly diagram.” However, solar activity has recently been found to be slightly asynchronous between the northern and southern hemispheres (Donner & Thiel 2007; Zolotova et al. 2010; Li et al. 2008, 2010; Deng et al. 2013a,b), and the N-S asymmetry of solar activity is related to the N-S phase difference of solar activity (Waldmeier 1957, 1971; Temmer et al. 2006). It is well known that during the Maunder minimum a unique sunspot asymmetry was observed. Sunspots were registered only in the southern hemisphere (Zolotova & Ponyavin 2007). Li et al. (2010) found that the flare index shows a slight phase asynchrony between the northern and southern hemispheres by using wavelet transform methods. If asynchrony sometimes occurs, it disappears rather rapidly during a solar cycle. The N-S asynchrony of dynamical processes is an important topic for understanding the origin and evolution of active regions on the Sun and their various manifestations in the solar corona (Zolotova & Ponyavin 2007; Li et al. 2010).

Although many active solar phenomena are used to investigate the N-S asymmetry and N-S asynchrony of solar activity, few characteristics are known about the relationship between these two features. An understanding of complexity in the long-term solar flare index in the northern and southern hemispheres may provide insight into the complex dynamics of the solar magnetic field in the two hemispheres. In the present study, we investigate the hemispheric asymmetry and asynchrony of the flare index, as well as the relationship between the two. In Section 2 we present the data set of the flare index; the analytic methods as well as the results are presented in Sections 3 and 4 respectively, and in the final Section, the main conclusions and discussions are given.

## 2 DATA DESCRIBING THE FLARE INDEX

The data describing the flare index in the northern and southern hemispheres are used to investigate the long-term hemispheric variation of the flare index. The flare index is calculated by Atac & Ozguc from Bogazici University’s Kandilli Observatory, and can be downloaded from the website[1]. Flare index is roughly proportional to the total energy emitted by a flare. The quantitative flare index is introduced by Kleczek (1952), and a detailed definition of the flare index can be found in Özgüç et al. (2003).

The upper and lower panels of Figure 1 show the flare index in the northern and southern hemispheres respectively for the time interval January 1966 - December 2010. The two time series are smoothed by a 13-point running average method. From the figure, the flare index varies with time in the hemispheres in different ways. The figure shows that (1) the northern and southern hemispheric flare indices never peak at the same time, and the flare index in the northern hemisphere peaks earlier in all the four solar cycles than that in the southern hemisphere, implying that the flare index is asynchronous in the northern and southern hemispheres; (2) the flare index develops with different strengths in the two hemispheres, and the amplitude of the flare index is asymmetrically distributed in the northern and southern hemispheres.

## 3 N-S ASYMMETRY OF FLARE INDEX

There are numerous papers describing the N-S asymmetry of solar activity. It can be calculated as the difference between indices $N$ and $S$ of solar activity

$$A_{\rm asy} = N - S\,. \quad (1)$$

This is the definition of absolute N-S asymmetry. The $N$ and $S$ stand for the distributions of solar activity corresponding to the northern and southern hemispheres respectively.

[1] *http://www.koeri.boun.edu.tr/astronomy*

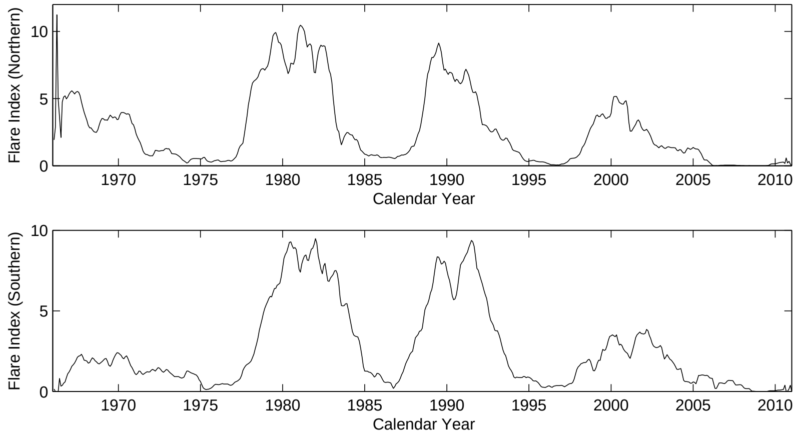


**Fig. 1** The distribution of the flare index in the northern (*upper panel*) and southern (*bottom panel*) hemispheres for the time interval 1966 January to 2010 December.

Newton & Milsom (1955) proposed a normalized measure of solar N-S asymmetry

$$N_{\rm asy} = \frac{N - S}{N + S} \, . \tag{2}$$

From 1966 January to 2010 December, the total of the flare index values are 1493.92 for the northern hemisphere and 1412.73 for the southern hemisphere. The absolute and normalized N-S asymmetries are 81.19 and 2.79% respectively, which suggests that the dominant hemisphere of the flare index is the northern hemisphere during the considered time interval. Furthermore, to verify whether the absolute and normalized asymmetry values of the flare index show statistical significance or not, a paired Student's t-test is used to check its N-S asymmetry. The Student's t-test is suitable for a non-integer, one-dimensional time series (Carbonell et al. 2007). The characteristic statistic $t$ is expressed as

$$t = \frac{\sum |D_i|/n}{\sqrt{\frac{\sum {D_i}^2 - \sum D_i^2/n}{n(n-1)}}} \, . \tag{3}$$

where $D_i$ is the difference of paired values and $n$ represents the number of elements that we have in each of the groups in which we split the corresponding time series, with $n - 1$ being the number of degrees of freedom. The most important feature of the Student's t-test is that the value of the statistic $t$ does not change when the units are changed. In the present study, we split the flare index into 45 groups, and each group includes data from one calendar year, so the number of elements in each group is thus 12. The statistic $t$ in each of the groups with hemispheric asymmetry of the flare index is shown in Figure 2. From Figure 2, we find that the confidence level of the statistic $t$ is $>$99% for 20% of the groups, between 90% and 99% for 71% of the groups, and smaller than 90% for 9% of the groups. Therefore, the N-S asymmetry of the flare index is a real phenomenon and the dominant hemisphere is the northern hemisphere.

Figure 3 shows the normalized and absolute N-S difference of the flare index from 1966 January to 2010 December; the vertical solid (dashed) lines mark the minimum (maximum) of the solar cycles. The figure shows that the N-S asymmetry of the flare index exhibits a long-term persistence, which means that it is a real phenomenon and not the result of random fluctuations.

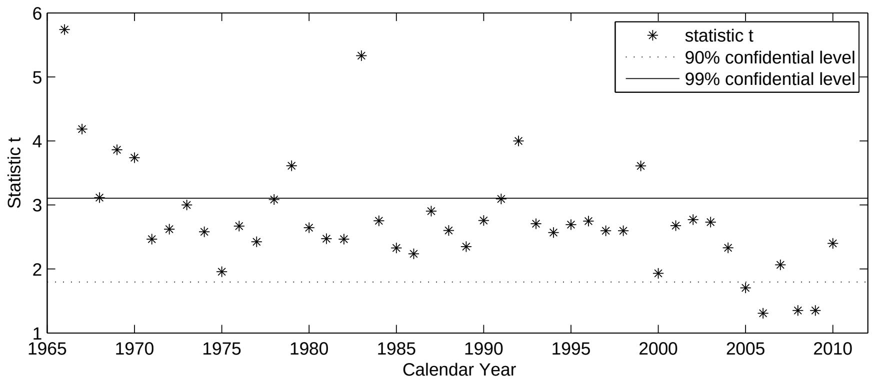


**Fig. 2** Characteristic statistic $t$ for each of the groups with hemispheric asymmetry of the flare index. The solid and dotted lines represent the 99% and 90% confidence level of the statistic $t$.

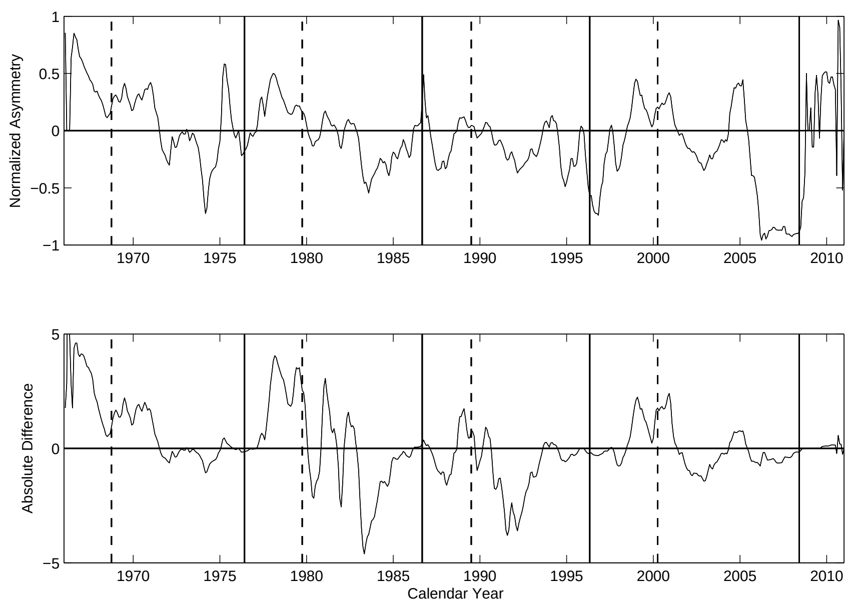


**Fig. 3** The normalized (*upper panel*) and absolute (*lower panel*) asymmetry of the flare index over the time interval 1966 January to 2010 December. The vertical solid (dashed) lines mark the minimum (maximum) of sunspot cycles. The two curves are smoothed by a 13-point running average.

## 4 N-S ASYNCHRONY OF FLARE INDEX

As pointed out by White & Trotter (1977), a graphical presentation such as Figure 1 allows us to study the systematic asynchrony between the onset of solar activity in the northern and southern hemispheres. The cross-correlation analytic method (Deng et al. 2011b) and cross-wavelet transform analysis (Li et al. 2010; Deng et al. 2013a) are used to study the N-S asynchrony of the flare index.

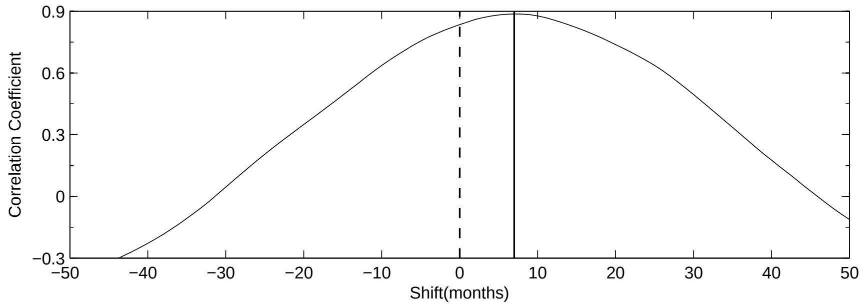


**Fig. 4** Cross-correlation coefficients between the flare index in the two hemispheres as a function of shifts, in which the abscissa indicates the shifts of the flare index in the northern hemisphere with respect to that in the southern hemisphere, with positive (negative) values representing forward (backward) shifts.

We calculate the cross-correlation coefficient for the leading and lagging shifts between the numbers of the flare index in the northern and southern hemispheres. Figure 4 shows the result of the cross-correlation coefficients between the flare index in the northern and that in the southern one. The abscissa indicates the shift of the northern hemispheric flare index with respect to the southern hemispheric flare index, with positive (negative) values representing forward (backward) shifts. From the figure, the best (positive) correlation between the flare index in the two hemispheres, with a correlation coefficient of 0.8867, occurs when the flare index in the northern hemisphere has a forward shift of seven months with respect to that in the southern hemisphere. From a statistical point of view, the cross-correlation coefficient obtained above is highly significant at the 99% confidence level. The correlation coefficient between the flare index in the two hemispheres with no shift is 0.8348. More importantly, we have to consider the errors in the correlation coefficient. The typical standard deviation in a correlation coefficient is $\sqrt{1/nu}$, where $nu$ is the degree of freedom. For the current set this will be 0.043. The difference between the correlation coefficients at seven and zero is slightly larger than this and hence the flare index in the northern hemisphere begins earlier than that in the southern hemisphere.

Although the cross-correlation analytic method shows that the flare index in the northern hemisphere begins earlier than that in the southern hemisphere, it cannot provide a comprehensive study about the phase relation between the flare index in the two hemispheres. Wavelet analysis involves a transform from a one-dimensional time series to a diffuse two-dimensional time-frequency space for detecting the localized and quasi-periodic fluctuations (Torrence & Compo 1998). To find how the phase difference between the flare index in the two hemispheres varies with time, the cross-wavelet transform is employed to show the phase relationship between them. It can reveal similarities in the states of the two systems and allows us to study the synchronization or phase difference in two time series (Marwan et al. 2002). The cross-wavelet transform of two time series $X$ and $Y$ is defined as

$$W^{XY} = W^X W^{Y*} , \tag{4}$$

where $W^X(W^Y)$ is the continuous wavelet transform of the time series and $*$ denotes complex conjugation. The complex argument arg ($W^{XY}$) can be interpreted as a local relative phase between $X$ and $Y$ in time-frequency space, namely the difference in phase angle between $X$ and $Y$ (Grinsted et al. 2004).

In the present paper, the codes provided by Grinsted et al. (2004) are employed to show the cross-wavelet transform between the flare index in the northern and southern hemispheres, which is displayed in the upper panel of Figure 5. The relative phase relation is shown by arrows. Arrows point

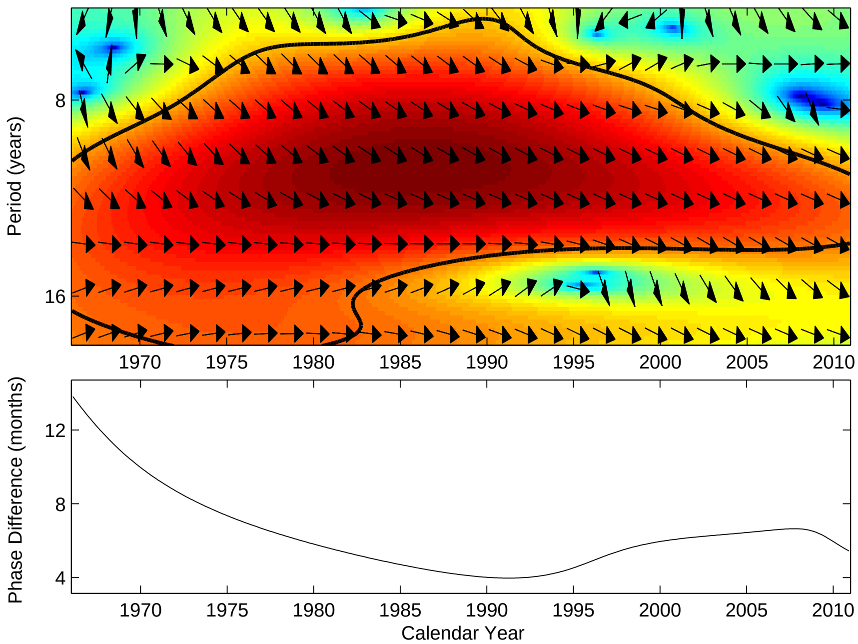


**Fig. 5** *Upper panel*: Cross-wavelet transform of the flare index in the northern hemisphere with respect to that in the southern one. The thick black contours indicate the 95% confidence level. *Bottom panel*: Phase difference at the period scales of 7–18 years varying with time. Positive values should be interpreted as the flare index in the northern hemisphere leading that in the southern one.

to the right when processes are in phase and to the left when they are in anti-phase. If an arrow points up (down), then the flare index in the northern hemisphere lags (leads) that in the southern one. By studying the phase differences at different time scales of sunspot areas in the northern and southern hemispheres by means of nonlinear analysis techniques, Zolotova & Ponyavin (2007) and Donner & Thiel (2007) found that the low-frequency components around the periodic scales of 8-14 years can be considered as a long-term trend and the high-frequency modes at the time scales less than 8 years are a stochastic component that is not random but rather modulated by amplitude. Taking very small or very large reference time scales into account should lead to non-coherent behavior of the phase variables assigned to the hemispheric flare index at these respective time scales. Therefore, we focus attention on periodicities at 7–18 years because these areas are located at the 95% confidence level. From the upper panel of Figure 5, the arrows have a small angle in the direction of right, pointing down for all time points during the time scales around 7–18 years. Over the long-term, the flare index in the northern hemisphere should lead that in the southern one.

Furthermore, we calculate the average of relative phase differences over periodic scales of 7–18 years for all time points in the considered time interval, which is shown in the bottom panel of Figure 5. Here, such a phase difference at a certain time point is calculated as the mean value of all phase differences at the period scale from the beginning to the end of the considered periodic scales. From the bottom panel of Figure 5, the relative phase differences between the flare indices in the two hemispheres are always positive in the considered time interval, indicating that the monthly flare index in the northern hemisphere should lead that in the southern hemisphere. The figure also shows that the relative phase difference varies from 4 months to 14 months, and the mean phase difference is about 6.36 months. The results obtained confirm the results given by the cross-correlation analytic method.

It is well known that solar flare activity is significantly delayed with respect to sunspot activity by several months in a hierarchical manner (Wheatland & Litvinenko 2001; Temmer et al. 2003; Yan et al. 2011; Du & Wang 2012). It is interesting that the phase difference of flare index between the two hemispheres is near that of the flare index with respect to sunspot activity, which may be related to the processes of accumulation and dissipation of magnetic energy from the lower to the upper atmosphere of the Sun (Du 2011a,b, 2012; Fang 2011). Wheatland & Litvinenko (2001) presented a detailed model for energy balance in a flaring corona. They assumed that the magnetic free energy in the corona satisfies a continuity equation and the flare rate increases with the stored energy in the corona. They stated that both the flaring rate and free energy of the system should lag behind the sunspot numbers under a certain initial value of the energy supply rate. Du (2011b) and Du & Wang (2012) proposed an integral response model to study the correlation of solar flare activity with both sunspot and geomagnetic activity, and the average time delay of solar flares with respect to sunspot activity in their model is about 8 months. Because the model proposed by Du (2011b) can be used to account for several unexplained phenomena, we will perform a detailed analysis to detect the phase asynchrony between solar flare activity and sunspot activity in the future.

## 5 CONCLUSIONS AND DISCUSSION

The asymmetrical phenomenon of solar activity exists in individual solar cycles, but it is not biased toward any hemisphere over a long-term. However, we find that the N-S asymmetry of the flare index is also present in a long-term range of observations. We infer that the long-term N-S asymmetry behavior is time-dependent, and it may be explained by its periodic characteristic. Vizoso & Ballester (1990), Ataç & Özgüç (1996) and Li et al. (2002) suggested a long-term characteristic time scale of about 8 or 12 solar cycles exists in the N-S asymmetry, and the dominant hemisphere of solar activity regularly varies with solar cycles. Some other periods of N-S asymmetry are also obtained by different authors (Knaack et al. 2004; Ballester et al. 2005). Because most periods reported are similar to that of the Schwabe solar cycle, the N-S asymmetry of solar activity is likely to be related to dynamo action.

It is interesting to note that the dominant hemisphere is the phase-leading hemisphere of the flare index, which suggests that the N-S asynchrony of the flare index is related to the N-S asymmetry of the flare index. Zolotova et al. (2010) suggested that the hemispheric asynchrony is found to be anti-correlated with the latitudinal distribution of the sunspots. By studying the daily sunspot area and its latitudinal variations during the period from 1874 to 2009, Cho & Chang (2011) stated that the N-S asymmetry of the sunspot areas and its latitudinal variation are consistently regulated by one single mechanism. Thus we reckon that there is an intrinsic relationship among the N-S asymmetry and N-S asynchrony, as well as the latitudinal variations of solar activity. Further study is needed. We hope that our results may be instructive in speculation on the physical origin of flare energy storage and dissipation, and suggest further research be conducted on the physical mechanisms of the solar cycle and active phenomena.

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## References

Ataç, T., & Özgüç, A. 1996, Sol. Phys., 166, 201
Ballester, J. L., Oliver, R., & Carbonell, M. 2005, A&A, 431, L5
Carbonell, M., Terradas, J., Oliver, R., & Ballester, J. L. 2007, A&A, 476, 951
Cho, I.-H., & Chang, H.-Y. 2011, Journal of Astronomy and Space Sciences, 28, 1
Deng, L.-H., Qu, Z.-Q., Liu, T., & Huang, W.-J. 2011a, Journal of Korean Astronomical Society, 44, 209
Deng, L. H., Song, J. Y., Xiang, Y. Y., & Tang, Y. K. 2011b, Journal of Astrophysics and Astronomy, 32, 401
Deng, L. H., Qu, Z. Q., Yan, X. L., Liu, T., & Wang, K. R. 2012, Journal of Astrophysics and Astronomy, 33, 221
Deng, L. H., Qu, Z. Q., Yan, X. L., & Wang, K. R. 2013a, RAA (Research in Astronomy and Astrophysics), 13, 104
Deng, L. H., Qu, Z. Q., Liu, T., & Huang, W. J. 2013b, Advances in Space Research, 51, 87
Donner, R., & Thiel, M. 2007, A&A, 475, L33
Du, Z. 2012, Sol. Phys., 278, 203
Du, Z. L. 2011a, Annales Geophysicae, 29, 1005
Du, Z. L. 2011b, Annales Geophysicae, 29, 1331
Du, Z.-L., & Wang, H.-N. 2012, RAA (Research in Astronomy and Astrophysics), 12, 400
Fang, C. 2011, RAA (Research in Astronomy and Astrophysics), 11, 1377
Gao, P. X., Li, Q. X., & Zhong, S. H. 2007, Journal of Astrophysics and Astronomy, 28, 207
Gao, P.-X., Li, K.-J., & Shi, X.-J. 2009, MNRAS, 400, 1383
Grinsted, A., Moore, J. C., & Jevrejeva, S. 2004, Nonlinear Processes in Geophysics, 11, 561
Kleczek, J. 1952, Bulletin of the Astronomical Institutes of Czechoslovakia, 3, 52
Knaack, R., Stenflo, J. O., & Berdyugina, S. V. 2004, A&A, 418, L17
Li, K. J., Wang, J. X., Xiong, S. Y., et al. 2002, A&A, 383, 648
Li, K. J., Liu, X. H., Zhan, L. S., et al. 2003, New Astron., 8, 655
Li, K. J., Gao, P. X., Zhan, L. S., Shi, X. J., & Zhu, W. W. 2008, MNRAS, 391, L34
Li, K.-J., Liang, H.-F., & Feng, W. 2010, RAA (Research in Astronomy and Astrophysics), 10, 1177
Marwan, N., Thiel, M., & Nowaczyk, N. R. 2002, Nonlinear Processes in Geophysics, 9, 325
Newton, H. W., & Milsom, A. S. 1955, MNRAS, 115, 398
Oliver, R., & Ballester, J. L. 1994, Sol. Phys., 152, 481
Özgüç, A., Ataç, T., & Rybák, J. 2003, Sol. Phys., 214, 375
Temmer, M., Veronig, A., & Hanslmeier, A. 2003, Sol. Phys., 215, 111
Temmer, M., Rybák, J., Bendík, P., et al. 2006, A&A, 447, 735
Torrence, C., & Compo, G. P. 1998, Bulletin of the American Meteorological Society, 79, 61
Verma, V. K. 1987, Sol. Phys., 114, 185
Vizoso, G., & Ballester, J. L. 1990, A&A, 229, 540
Waldmeier, M. 1957, ZAp, 43, 149
Waldmeier, M. 1971, Sol. Phys., 20, 332
Wheatland, M. S., & Litvinenko, Y. E. 2001, ApJ, 557, 332
White, O. R., & Trotter, D. E. 1977, ApJS, 33, 391
Xie, J.-L., Shi, X.-J., & Xu, J.-C. 2012, RAA (Research in Astronomy and Astrophysics), 12, 187
Yan, X. L., Qu, Z. Q., & Xu, C. L. 2008, ApJ, 682, L65
Yan, X. L., Deng, L. H., Qu, Z. Q., & Xu, C. L. 2011, Ap&SS, 333, 11
Zhang, L. Y., Wang, H. N., Du, Z. L., Cui, Y. M., & He, H. 2007, A&A, 471, 711
Zolotova, N. V., & Ponyavin, D. I. 2007, Sol. Phys., 243, 193
Zolotova, N. V., Ponyavin, D. I., Arlt, R., & Tuominen, I. 2010, Astronomische Nachrichten, 331, 765