J. Astrophys. Astr. (2011) **32,** 401–409

The Relative Phase Asynchronization between Sunspot Numbers and Polar Faculae

L. H. Deng[1,2,*], J. Y. Song[1,2], Y. Y. Xiang[1] & Y. K. Tang[3]

[1]*National Astronomical Observatories/Yunnan Astronomical Observatory, Chinese Academy of Sciences, P. O. Box 110, 650011 Kunming, People's Republic of China.*
[2]*Graduate School of the Chinese Academy of Sciences, ShijingShan Block, 100049 Beijing, People's Republic of China.*
[3]*Department of Physics, Dezhou University, 253023 Dezhou, People's Republic of China.*
**e-mail: bench@ynao.ac.cn*

Received 2010 December 27; accepted 2011 July 1

Abstract. The monthly sunspot numbers compiled by Temmer *et al.* and the monthly polar faculae from observations of the National Astronomical Observatory of Japan, for the interval of March 1954 to March 1996, are used to investigate the phase relationship between polar faculae and sunspot activity for total solar disk and for both hemispheres in solar cycles 19, 20, 21 and 22. We found that (1) the polar faculae begin earlier than sunspot activity, and the phase difference exhibits a consistent behaviour for different hemispheres in each of the solar cycles, implying that this phenomenon should not be regarded as a stochastic fluctuation; (2) the inverse correlation between polar faculae and sunspot numbers is not only a long-term behaviour, but also exists in short time range; (3) the polar faculae show leads of about 50–71 months relative to sunspot numbers, and the phase difference between them varies with solar cycle; (4) the phase difference value in the northern hemisphere differs from that in the southern hemisphere in a solar cycle, which means that phase difference also existed between the two hemispheres. Moreover, the phase difference between the two hemispheres exhibits a periodical behaviour. Our results seem to support the finding of Hiremath (2010).

Key words. Sun: sunspot—faculae—asynchronization.

1. Introduction

Since polar faculae were discovered by the German amateur astronomer Weber (1865), who was the first to notice that maximum polar faculae activity occurred at minimum sunspot activity (Makarov & Makarova 1996), the phase relation between the polar faculae and sunspot activity has been extensively studied, but it is a controversial problem in history. Kiepenheuer (1953) showed that the solar cycle has no pronounced relationship with the polar faculae, and does not appear to be associated with the polar prominences in any way. Hagino *et al.* (2004) found that the phase relation between them is time-dependent. Saito & Tanaka (1960) showed an evident anti-correlation between polar faculae and sunspot activity in that the maximum of the former seems to take place one year ahead of the minimum of the latter. Sheeley (1964, 1991) found a 90° phase-shift and claimed that the faculae activity lag behind the sunspot numbers. But Makarov *et al*. (1987, 1996) obtained an opposite result that the monthly numbers of polar faculae lead the sunspot areas with a time-shift of about 6 years. Li *et al*. (2002) found that the faculae activity is highly correlated with the sunspot numbers with a time-shift of 51 months into the following sunspot cycle. Li *et al*. (2006) considered that the activity of polar faculae should lead sunspot activity in time phase and the time-lead phenomenon rest with the dynamo theory. In other words, it is basically confirmed that polar faculae and sunspot activity are not in phase, and the former should lead the latter, but the time-shift between them is not reported consistently by different authors, and we still do not know why there is a time-lead phenomenon between the occurrence of polar faculae and sunspot activity. It should be pointed that all the above-mentioned results are based on the long time spans, so it is necessary to analyse the phase relationship between the activity of polar faculae and the sunspot activity in a short time interval, i.e., individual solar cycle.

The activity of the northern and southern hemispheres are only weakly coupled by studying the North–South asymmetry in the predominant rotation periods of photosphere magnetic fields, the global evolution in a solar cycle as well as time scales related to the Sun's rotation (Antonucci *et al*. 1990; Henney & Harvey 2002; Temmer *et al*. 2002, 2003). North–South asymmetry is also reported for polar faculae in each of the solar cycles (Li *et al*. 2002). The delay phenomena might arise from overlapping effects of the activity of both hemispheres, which in general do not evolve in phase. To account for this possibility, we study the phase relation between occurrence of polar faculae and sunspot numbers not only for the total solar disk, but also individually for the northern and southern hemispheres.

The aim of the present paper is to investigate whether the time-lead phenomenon between the polar faculae and the sunspot numbers is indeed a distinct feature of solar activity, and to analyse the phase difference for which regular characteristic on polar faculae occurrence is available during all solar cycles, viz., cycles 19 to 22. We adopt the usual cross-correlation analysis method as Hagino *et al*. (2004) and Li *et al*. (2002, 2006). In Section 2 the observational data sets and analysis method are described, while the results are presented in Section 3. Finally, Section 4 contains a summary of the main conclusions and discussions.

2. Data and method

We employ monthly mean sunspot numbers together with monthly numbers of polar faculae from March 1954 to March 1996. The period fully covers solar cycle 19 (March 1954–August 1964), cycle 20 (September 1964–April 1976), cycle 21 (May 1976–July 1986) as well as cycle 22 (August 1986–March 1996). The time span is analyzed in detail, considering not only the entire solar disk but also the northern and southern hemispheres separately. The data used in the present paper are as follows:

1. The observational data of polar faculae activity in the northern and southern hemispheres come from the Zeiss 20-cm refractor at Mitaka of the National

Astronomical Observatory of Japan (NAOJ), which can be downloaded from NAOJ's web site http://solarwww.mtk.nao.ac.jp/en/db_faculae.html. The data sets gave the 13-months running averages (smoothed data) from February 1952 to June 1998 in each solar hemisphere at three latitude intervals (50°–60°, 60°–70°, 70°–90°), respectively.

2. The smoothed monthly sunspot numbers in the northern and southern hemispheres from January 1945 to December 2004 were compiled by Temmer *et al.* (2006) (http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/447/735).

Due to the rotation axis of the Sun tipped by about 7 degrees with respect to the earth, the polar faculae counts show strong annual variation, and the polar region is most visible in September for northern hemisphere and March for southern hemisphere. The 13-month running averages can remove this apparent visibility of the polar regions, and also compensate for seasonal variations in observing conditions (Hagino *et al.* 2004). So in the present article, the counts of polar faculae and sunspot numbers have been smoothed by a 13-month running method, and we extract the sunspot numbers from March 1954 to March 1996 as polar faculae.

Sakurai (1998) showed that the polar faculae observed at the latitudinal band 50°–60° should be made up of two parts: one (polar faculae) belonging to the activity cycle of the polar faculae and the other (active region faculae) to the sunspot activity cycle, and the two parts are anti-correlated with each other (Li *et al.* 2002). Therefore, we take account of the polar faculae only at 60°–70° and 70°–90° bands of the two hemispheres, while the polar faculae at the latitudinal band 50°–60° are not taken into account. Thus, we combine the numbers of polar faculae at the latitudinal bands 60°–70° and 70°–90° respectively into the numbers of polar faculae for the total solar disk and for two hemispheres. Figure 1 shows the 13-months running averages of the polar faculae and the monthly smoothed sunspot numbers in the northern hemisphere, southern hemisphere and the total solar disk, respectively. The minimum and maximum of each solar cycle are indicated by solid and dashed lines, respectively. Note that the cycle maxima (minima) are defined on the basis of the sunspot activity, and therefore do not coincide with the maxima (minima) of polar faculae activity. As Fig. 1 shows, the polar faculae activity is in anti-phase with the sunspot activity: a new cycle of polar faculae activity begins approximately at the maximum of a sunspot cycle and ends approximately at the maximum of the neighboring solar cycle. Thus, the figure indicates that the activity of the polar faculae has a phase-shift with the sunspot numbers for total solar disk and also for both hemispheres in solar cycles 19, 20, 21 and 22.

To study the phase relationship between the polar faculae activity and the sunspot numbers, we used cross-correlation analysis to investigate the polar faculae with respect to the sunspot numbers in each of the solar cycles, for the total solar disk and for two hemispheres, as was adopted by Li *et al.* (2002, 2006) and Hagino *et al.* (2004). The cross-correlation coefficient $R(\Delta)$ between the counts of polar faculae $P(i)$ and sunspot numbers $S(i)$ is defined as

$$R\,(\Delta) = \frac{\sum_{i=1}^{N}\,[P(i) - \langle P\rangle]\,[(S(i+\Delta) - \langle S\rangle\,]}{(N-1)\,\delta_P\delta_S},$$

where δ_P and δ_S represent the standard deviations in $P(i)$ and $S(i)$, respectively, and $\langle\quad\rangle$ stands for mean values. Positive Δ means that the time series of polar faculae

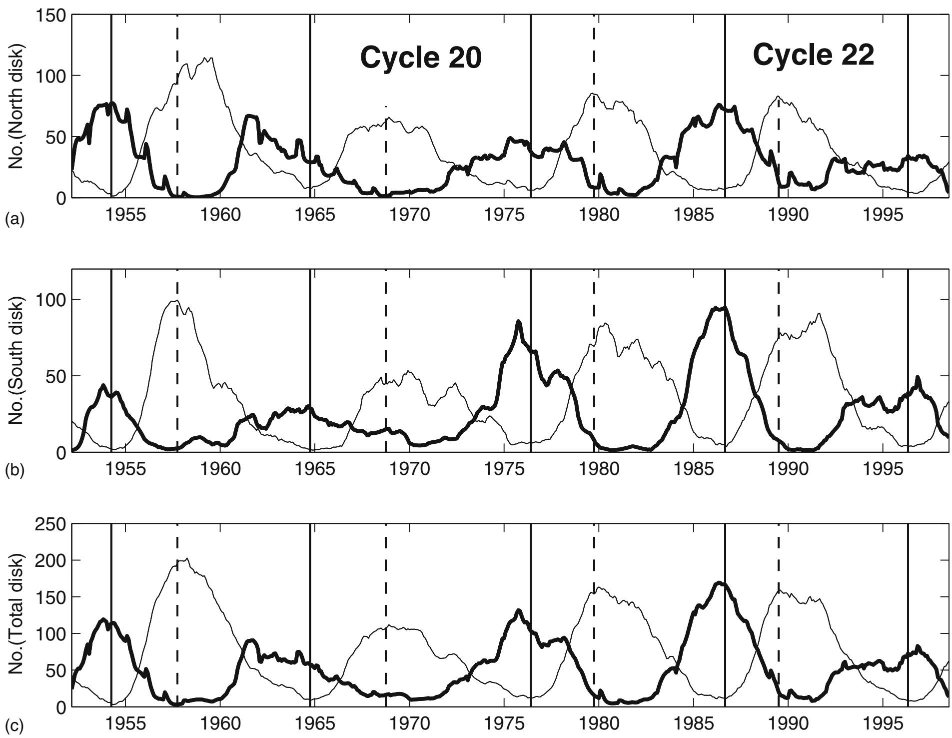

Figure 1. The smoothed monthly sunspot numbers (solid black line) and polar faculae (bold solid black line), in the northern hemisphere (**a**), southern hemisphere (**b**) and total solar disk (**c**), respectively. The polar faculae numbers multiply by 7. The vertical solid and dashed lines represent the minimum and maximum of each solar cycle, respectively.

activity leads with respect to sunspot activity time series (Hagino *et al*. 2004; Yan *et al*. 2011). We computed the correlation coefficient for the leading and lagging shifts between polar faculae activity and sunspot numbers for the total solar disk and for two hemispheres, and then compared the maximum correlation coefficients of the leading and lagging shifts.

3. Results

In order to determine the phase relationship between the polar faculae counts and sunspot numbers, the cross-correlation analysis between them has been done in solar cycles 19, 20, 21 and 22. This analysis has been carried out for the entire solar disk as well as separately for both hemispheres, i.e., we compared monthly numbers of polar faculae activity with monthly sunspot numbers that occurred on the entire solar disk, northern and southern hemispheres.

In Fig. 2, we show the outcome of a cross-correlation analysis between monthly numbers of polar faculae and relative sunspot numbers, for two hemispheres and for the total solar disk from solar cycles 19 to 22. The abscissa indicates the shift of the polar faculae numbers with respect to the sunspot numbers, with positive (negative)

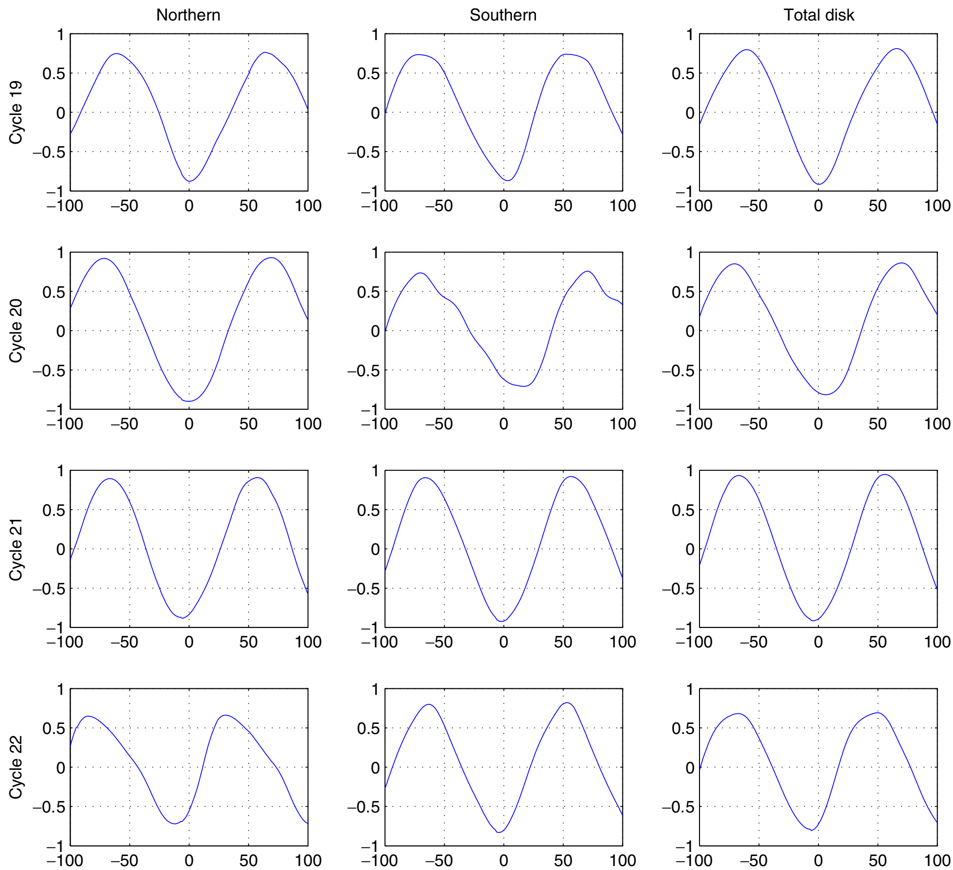

Figure 2. Cross-correlation coefficients derived from the monthly numbers of polar faculae and monthly sunspot numbers for two hemispheres and for the total solar disk during solar cycles 19 to 22. The abscissa indicates the shift of polar faculae numbers with respect to the sunspot numbers, with positive values representing forward shifts (towards the following sunspot cycle). The *left panels* refer to the activity in the northern hemisphere, the *middle panels* to the southern hemispheres, and the *right panels* to the total solar disk.

values representing forward (backward) shifts, i.e., toward the following (previous) sunspot cycle.

For solar cycle 19, the cross-correlation coefficient, calculated between sunspot numbers and polar faculae observed on the entire solar disk, shows that the largest positive coefficient with 0.810 when polar faculae shifted toward the following sunspot cycle by about 66 months, indicating a time-lead of polar faculae with respect to sunspot numbers. The secondary largest positive coefficient with 0.796 is almost as high as the first maximum when the polar faculae shifted toward the previous sunspot cycle by about 72 months. The best positive correlation coefficient of leading shifts is slightly larger than that of the lagging shifts. Considering both hemispheres separately, it can be seen that for the northern (southern) hemisphere the largest correlation coefficients with 0.762 (0,740) and 0.746 (0.734) when polar faculae shifted 64 (54) and 61 (72) months with respect to the following and the previous sunspot cycle, respectively. The above 6 correlation coefficients are significant at the 95% level. That is, for solar cycle 19, the results obtained for the entire solar disk and for the two hemispheres give a consistent result: the correlation coefficients between polar faculae activity and the following sunspot activity are larger than those between polar faculae activity and the previous sunspot activity. In other words, the polar faculae activity should lead the sunspot numbers in time phase. Our result – the polar faculae activity begin 54–66 months earlier than sunspot numbers in the solar cycle 19, which confirms the findings of Li *et al.* (2002, 2006).

From Fig. 2, we found that the largest positive correlation occurs with a correlation coefficient of 0.862 (0.929, 0.756), 0.945 (0.908, 0.920), 0.691 (0.662, 0.821) when the polar facular count shifted toward the following sunspot cycle by about 70 (70, 71), 57 (58, 56), 50 (31, 53) months for total solar disk (northern hemisphere, southern hemisphere), in solar cycles 20, 21 and 22, respectively. The secondary largest positive correlation occurs with a correlation coefficient of 0.849 (0.918, 0.735), 0.931 (0.892, 0.904), 0.681 (0.648, 0.800) when the polar facular count is shifted toward the previous sunspot cycle by about 70 (71, 70), 68 (65, 67), 68 (85, 63) months for the total solar disk (northern hemisphere, southern hemisphere), in solar cycles 20, 21 and 22, respectively. So, for the total solar disk and for both the hemispheres respectively, the polar faculae activity begin earlier than the sunspot activity during solar cycles 19 to 22. Our results strengthen the conclusion obtained by Li *et al*. (2002, 2006). Moreover, the phase difference between them exhibits a consistent behaviour for different hemispheres during different solar cycles, suggesting it to be a real phenomenon and not due to stochastic fluctuations.

Table 1 lists the largest positive coefficients and the corresponding values of phase difference between polar faculae with respect to following (previous) sunspot cycle. It can be seen from Table 1 that a characteristic time-lead exists between polar faculae and sunspot numbers in the range of 50–71 months, but these time-leads are different for different solar cycles, that is, the phase difference between them varies with time. Since the time range is divided into individual solar cycle and each hemisphere, the time-lead between polar faculae and sunspot numbers is obtained more accurately. In a solar cycle, the value of phase difference in the northern hemisphere differs from that in the southern hemisphere, which implies that the phase difference phenomenon also exists between two hemispheres. Li (2008) and Li *et al.* (2008) applied the cross-wavelet transform and wavelet coherence method to study the phase relationship between two hemispheres of polar faculae, and found that the

Table 1. The phase difference and the corresponding correlation coefficient between polar faculae and the neighbouring solar cycle for solar cycles 19–22. 'N', 'S', and 'T' indicate the northern, southern hemispheric and total solar disk, respectively. 'STF' and 'STP' represent the polar faculae *shift toward* the *following* and *previous* sunspot cycle.

	SC 19		SC 20		SC 21		SC 22	
	STF	STP	STF	STP	STF	STP	STF	STP
N	64(0.762)	−61(0.746)	70(0.929)	−71(0.918)	58(0.908)	−65(0.892)	31(0.662)	−85(0.648)
S	54(0.740)	−72(0.734)	71(0.756)	−70(0.735)	56(0.920)	−67(0.904)	53(0.821)	−63(0.800)
T	66(0.810)	−60(0.796)	70(0.862)	−70(0.849)	57(0.945)	−68(0.931)	50(0.691)	−68(0.681)

Table 2. Correlation coefficient between polar faculae activity and sunspot numbers in the northern hemisphere, southern hemisphere and the total solar disk in each of the solar cycles (SC) 19 to 22, respectively.

	SC 19	SC 20	SC 21	SC 22
Northern	−0.877	−0.900	−0.835	−0.554
Southern	−0.854	−0.618	−0.919	−0.802
Total disk	−0.917	−0.788	−0.892	−0.726

activity of the polar faculae in the northern hemisphere slightly leads the southern hemisphere in different time ranges. Thereby, they inferred that the Schwabe period length in one hemisphere actually differs from that in the other hemisphere, this being one of the possible reasons which lead to phase asynchrony of the hemispheric polar faculae activity. Their results confirm the conjecture derived by us. From Table 1, we found an interesting phenomenon – if the phase difference in the northern hemisphere is larger than that in the southern hemisphere in a cycle, then the difference in the southern hemisphere will be larger than that in the northern hemisphere in the neighboring solar cycle – which implies that the phase difference between two hemispheres exhibits a periodical behaviour. Li (2009) found an eight-cycle period to exist in phase-shift between two hemispheres by using five solar activity indices. As the record of polar faculae is too short, our result merely inferred that a periodical behaviour should exist, but we can not clearly confirm this phenomenon. For a more unambiguous analysis, a worldwide observations of polar faculae over longer periods are needed in the future.

Many authors reported that the polar faculae are in anti-correlation with sunspot activity, but their results were based on long time spans and did not present the correlation coefficient between them. Therefore, it is necessary to compute the correlation coefficient between the activity of the polar faculae and the sunspot activity in individual solar cycles. The cross-correlation coefficient for the total solar disk and for two hemispheres in each of the solar cycles, respectively, are listed in Table 2. It can be seen from Table 2 that the correlation coefficients between polar faculae and sunspot numbers are negative, and the absolute values of correlation coefficient are larger than 0.8. The below 12 correlation coefficients are significant at the 95% level, which means that the highly inverse correlation is not only a long-term behaviour, but also exists for short time range. Furthermore, these correlation coefficients differ from cycle to cycle, that is, the correlation strength is different during different solar cycles and different hemispheres.

4. Discussions and conclusions

In the present study, we analysed the phase relationship between the polar faculae counts and the sunspot numbers for the total solar disk and for both hemispheres in solar cycles 19, 20, 21 and 22. The main results obtained are as follows:

1. The polar faculae activity begin earlier than sunspot activity during solar cycles 19 to 22. Thus, our result strengthened the conclusions obtained by Li *et al.*

(2002, 2006). Moreover, the phase difference between them exhibits a consistent behaviour for different hemispheres during different solar cycles, which suggests that it should be regarded as a real phenomenon and not due to stochastic fluctuations.

2. The cross-correlation coefficients between polar faculae and sunspot numbers are highly negative for the total solar disk and for both hemispheres, when the time range are divided into individual solar cycles, which implies that the inverse correlation between them is not only a long term behaviour, but also exists for short time range.
3. The polar faculae show leads of about 50–71 months relative to sunspot numbers. These time-leads are different for different solar cycles. That is, the phase difference between them varies with solar cycle.
4. The phase difference value between polar faculae and sunspot numbers in the northern hemisphere differs from that in the southern hemisphere, which implies that the phase difference phenomenon also existed between northern and southern hemispheres. Moreover, if the phase difference in the northern hemisphere is larger than that in the southern hemisphere in a cycle, then the difference in the southern hemisphere will be larger than that in the northern hemisphere in the neighboring solar cycle. This implies that the phase difference between two hemispheres exhibits a periodical behaviour.

As we know, the activity of polar faculae and sunspot numbers represent the high-latitude (over about 60°, near the pole) and the low-latitude (below 50°) solar activity, respectively (Tanaka 1964; Sakurai 1998; Riehokainen *et al*. 2001; Li *et al*. 2002, 2006). Based on the dynamo theory and the observation of large-scale magnetic fields, Li *et al.* (2006) considered that the high-latitude solar activity should lead the low-latitude solar activity in time phase. In fact, although the turbulent dynamo models explain qualitatively many of the observed solar cycle and activity phenomena, there are several difficulties and limitations in their application to the solar cycle and activity phenomenon (Hiremath and Gokhale 1995; Hiremath 2001, 2010 and references therein). Compared to the turbulent dynamo mechanism, the MHD oscillation mechanism has more advantages. Due to the poloidal part of the steady field structure, the Alfven wave perturbations excited in the solar core travel first to the poles in both hemispheres and later reaches the equator. While traveling towards the surface, the Alfven wave perturbations along the weak poloidal field structure in turn perturb the embedded strong toroidal field structure producing sunspots, which travel to the surface due to buoyancy along isorotational contours (Hiremath 2010). Thus, the polar faculae (high-latitude solar activity) should begin earlier than sunspot activity (low-latitude solar activity), i.e., there is a phase difference between the activity of polar faculae and the sunspot numbers. Furthermore, according to the MHD oscillation mechanism, the phase lag between polar solar activity and equatorial solar activity should be $\pi/2$ solar radians, owing to the length of sunspot cycle also varying from 9 to 12.5 years (Hiremath 2008). Correspondingly, the phase difference between the activity of polar faculae and sunspot numbers should be in the range of 54 to 75 months. Thus our results – the polar faculae show leads of about 50–71 months relative to sunspot numbers, and the phase difference between them varies with solar cycle – can be explained by Alfven wave theory. In other words, our conclusions support the findings of Hiremath (2010) and their previous works.

Acknowledgements

The authors thank the anonymous referee for her/his careful reading of the manuscript and constructive comments that improved the original version. The data of polar faculae and sunspot numbers, used in the present paper, are all downloaded from the website. The authors would like to express their deep thanks to the staff of all the websites who provided the data for public to download. This work is supported by the National Natural Science Foundation of China (11003041), Yunnan Nature Science Foundation of China (2009CD120), Shandong Nature Science Foundation (2009ZRA14032), Dezhou University Foundation (402811), and the Chinese Academy of Sciences.

References

Antonucci, E., Hoeksema, J. T., Scherrer, P. H. 1990, *Astrophys. J.*, **360**, 296.
Hagino, M., Sakurai, K., Miyazawa, A. 2004, *ASP. Conf. Ser.*, **325**, 157.
Henney, C. J., Harvey, J. W. 2002, *Solar Phys.*, **207**, 199.
Hiremath, K. M., Gokhale, M. H. 1995, *Astrophys. J.*, **448**, 437.
Hiremath, K. M. 2001, *Bull. Astron. Soc. India.*, **29**, 169.
Hiremath, K. M. 2008, *Astrophys. Space Sci.*, **314**, 45.
Hiremath, K. M. 2010, *Sun Geosphere.*, **5**, 17.
Kiepenheuer, K. O. 1953, In: *The Sun*, (ed.) Kuiper, G. P. (Chicago: University of Chicago Press), p. 368.
Li, K. J., Irie, M., Wang, J. X., Xiong, S. Y., Yun, H. S., Liang, H. F., Zhan, L. S., Zhao, H. J. 2002, *Publ. Astron. Soc. Jpn*, **54**, 787.
Li, K. J., Gao, P. X., Zhan, L. S., Shi, X. J., Zhu, W. W. 2008, *Mon. Not. R. Astron. Soc.*, **391**, L34.
Li, K. J., Liang, H. F., Gao, P. X., Su, T. W. 2006, *Solar Phys.*, **236**, 185.
Li, K. J. 2009, *Solar Phys.*, **255**, 169.
Li, Q. X. 2008, *Solar Phys.*, **249**, 135.
Makarov, V. I., Makarova, V. V. 1987, *Soln. Dann. Byull.*, **3**, 62.
Makarov, V. I., Makarova, V. V. 1996, *Solar Phys.*, **163**, 267.
Riehokainen, A., Urpo, S., Valtaoja, E., Makarov, V. I., Makarova, V. V., Tlatov, A. G. 2001, *Astron. Astrophys.*, **366**, 676.
Saito, K., Tanaka, Y. 1960, *Publ. Astron. Soc. Jpn.*, **12**, 556.
Sakurai, T. 1998, *ASP. Conf. Ser.*, **140**, 483.
Sheeley, N. R., Jr. 1964, *Astrophys. J.*, **140**, 731.
Sheeley, N. R., Jr. 1991, *Astrophys. J.*, **374**, 386.
Tanaka, Y. 1964, *Publ. Astron. Soc. Jpn*, **16**, 336.
Temmer, M., Rybak, J., Bendik, P., Veronig, A., Vogler, F. 2006, *Astron. Astrophys.*, **447**, 735.
Temmer, M., Veronig, A., Hanslmeier, A. 2002, *Astron. Astrophys.*, **390**, 707.
Temmer, M., Veronig, A., Hanslmeier, A. 2003, *Solar Phys.*, **215**, 111.
Weber, F. 1865, *Wochenschrift fur Astron. Met. Geogr.*, **8**, 38 & 143.
Yan, X. L., Deng, L. H., Qu, Z. Q., Xu, C. L. 2011, *Astrophys. Space Sci.*, **333**, 11.