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The latitude of ephemeral regions as an indicator for solar-cycle strength

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Abstract. Digitized images of full-disk Ca K spectroheliograms from two solar observatories were used to study the cycle variation of ephemeral regions (ERs) over the ten solar cycles 14–23. We calculate the monthly averaged unsigned latitude of ERs and compare it with the annual sunspot number. We find that the average latitude of ERs can be used as a predictor for the strength of a solar cycle. For a short-term prediction ($dT \sim 1$–2 years), the maximum latitude of ERs (in the current cycle) defines the amplitude of that cycle (the higher the latitude of ERs, the larger the amplitudes of the sunspot cycle). For a long-term prediction ($dT \sim 1.5$ solar cycles), the latitude of ERs during the declining phase of the nth cycle determines the amplitude of the $(n+2)$th cycle (the lower the latitude of ERs, the stronger is the sunspot cycle). Using this latter dependency, we forecast the amplitude of sunspot cycle 24 to be at $W = 92 \pm 13$ (in units of annual sunspot number).

Key words. Sun: activity – Sun: chromosphere – Sun: faculae, plages – Sun: sunspots

1. Introduction

Historic data sets of full-disk Ca II K spectroheliograms observed from three observatories: Kodaikanal (KKL), Mount Wilson (MWO), and the National Solar Observatory at Sacramento Peak (NSO/SP) span about ten past solar cycles. Recently, these data were digitized and calibrated. In this study we use the KKL and NSO/SP data sets to explore the latitudinal distribution of ephemeral active regions (ERs) as a potential precursor of the amplitude of sunspot cycles. Images were acquired with the 0.5 Å wide exit slit of the spectroheliograph centered at $\lambda = 3933.67$ Å. The spatial resolution is approximately $1.2''$ pixel^{-1}. Further details on these data sets can be found in Tlatov et al. (2009). Flocculi and plages were identified using an intensity threshold as described in Tlatov et al. (2009). Isolated clusters of bright pixels (not connected with other clusters) were classified as independent flux elements, and the total number of elements and area of each element were computed for every image in our data set. Despite differences in the observations, floccular areas show good correlation between instruments and with sunspot number (Fig. 1). Tlatov et al. (2009) established a correlation between the total area of Ca K plages ($A_{\rm plage}$) and the area of sunspots ($A_{\rm sunspot}$), $A_{\rm plage} = (8.5 \pm 0.3) + (15 \pm$

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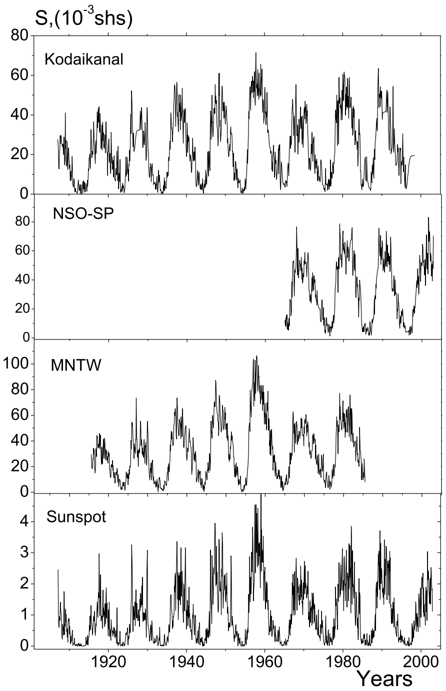

Fig. 1. Monthly averaged area of Ca II K plages derived from data from three observatories (three upper panels) and area of sunspots (lower panel).

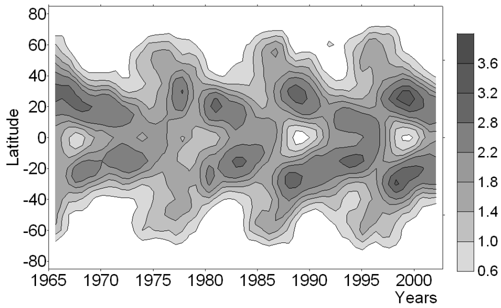

Fig. 2. Number of Ca II K ERs in the NSO/SP data as a function of time and latitude. Data corresponds to 3-month averages computed over 5° latitudinal intervals.

$0.25)A_{\mathrm{sunspot}}$, with a Pearson linear correlation coefficient of $R = 0.88$. The KKL data set is the longest of the three, while the NSO/SP set is the most recent. Given the good correlation between the KKL, MWO, and NSO/SP Ca II K data, we chose to use the Kodaikanal and NSO/SP observations for the following analysis.

2. Average latitude of Ca II K flocculi

We have selected a subset of mid-sized floccular elements with an area between 100 and 300 millionths of the solar hemisphere (MSH). Harvey & Martin (1973) classified elements with this area observed in Ca II K line as ERs. The majority of bright elements identified in Ca II K images correspond to chromospheric network elements; only a small fraction (~ 10%) matches ERs and plages. Furthermore, while the total number of bright elements does not vary with sunspot cycle, the number of ERs does exhibit (sunspot) cycle-like variations. Figure 2 displays the number of ERs found in the NSO/SP data as a function of time and latitude. Typically, the ER cycle starts at high latitudes of ~ 60 degrees and about 1–2 years before the sunspot cycle peaks. Hence, the ER cycle appears to be shifted w.r.t. the sunspot cycle: the number of ERs is lowest during the rising phase of a sunspot cycle, and it peaks in the tail of sunspot cycle when sunspot activity concentrates at the equatorial region.

In a next step, we calculated the average latitude of ERs

$$\bar{\theta} = \frac{1}{N}\sum_{i=1}^{N} |\theta_i|\,,$$

where N is the total number of ERs observed in a given month and θ_i is the latitude of an individual ER.

The average latitude of ephemeral regions shows a clear variation with the sunspot cycle (Fig. 3). ER latitudes peak during the rising phase of a sunspot cycle, approximately 1–2 years before the number of sunspots reaches its maximum. Examining Figs. 3 and 4 one may note a correlation between the maximum latitude $\bar{\theta}_1$ of ERs and the amplitude of the sunspot cycle: the higher the average latitude of ERs, the stronger the sunspot cycle. A similar tendency is also present in the butterfly diagram of sunspots (not shown): for stronger

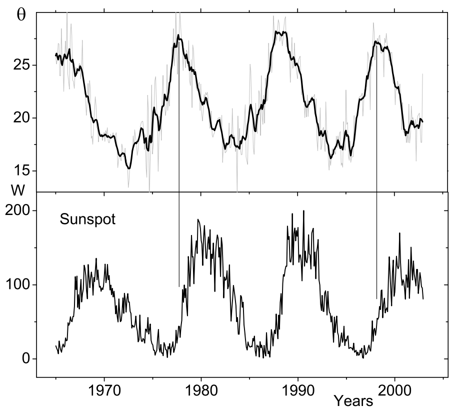

Fig. 3. Three months (upper panel, thin curve) and 12-months (thick curve) averaged latitude of Ca II K ERs derived from NSO/SP data and annual sunspot number (lower panel). Thin vertical lines demonstrate that ERs reach their maximum latitude a few years prior to sunspot maximum during the rising phase of a sunspot cycle.

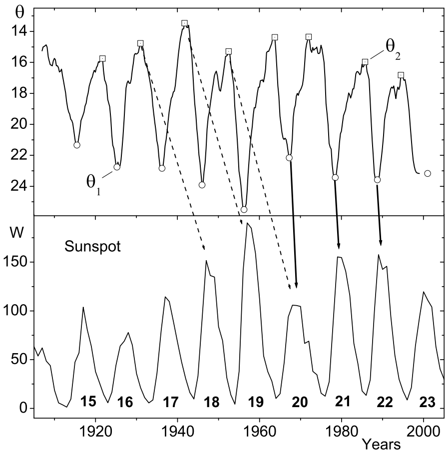

Fig. 4. Average latitude ($\bar{\theta}$, in degrees) of ERs (upper panel) and the sunspot number (W, lower panel). Open squares and circles mark local minima ($\bar{\theta}_{2i}$) and maxima ($\bar{\theta}_{1j}$) of ER latitudes. Dashed lines with arrowheads draw a correspondence between minimum latitude of ERs and maximum sunspot number. Solid lines with arrowheads show a correspondence between the maximum latitude of ERs and the maximum sunspot number. To see the pattern, compare the order of cycles and their amplitude with the order of minima and maxima of the average latitude of ERs.

cycles the first sunspots appear at higher latitudes, while for weaker cycles, the latitude at which early sunspots appear is lower. Figure 5 shows a correlation between the maximum latitude of ERs ($\bar{\theta}_1$) and the sunspot number (W). The corresponding the Pearson linear correlation coefficient is $R_{\theta 1} = 0.83$.

Interestingly, those minima in the average latitude of ERs ($\bar{\theta}_2$) that occur during the declining phase of the *n*th cycle correlate quite well with the amplitude of the $(n + 2)$th sunspot cycle. The dashed lines with arrowheads shown in Fig. 4 demonstrate this relation. Figure 6 displays the correlation between the minimum latitude of ERs ($\bar{\theta}_2$) and the sunspot number (W) with $R_{\theta 2} = 0.92$. This latter correlation allows to forecast the amplitude of a sunspot cycle for about one and a half solar cycles prior to its occurrence.

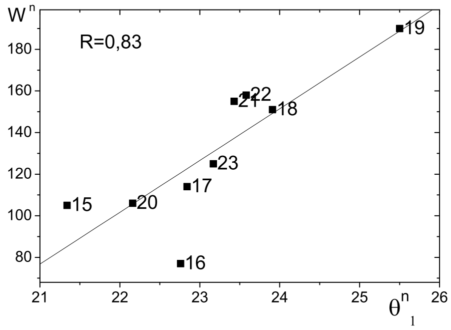

Fig. 5. Amplitude of *n*th sunspot cycle (annual sunspot number) as a function of maximum latitude (in degrees) of ERs during the rising phase of the same cycle. Solid line shows a linear approximation to the data, $W^n = (-445.782 \pm 146.000) + (24.884 \pm 6.289) \times \bar{\theta}^n_1$.

3. Discussion

Forecasting the strength of future solar cycles was attempted by a number of researchers (e.g., Ol' 1968; Javaraiah 2007). In our present study, we demonstrate that the average latitude

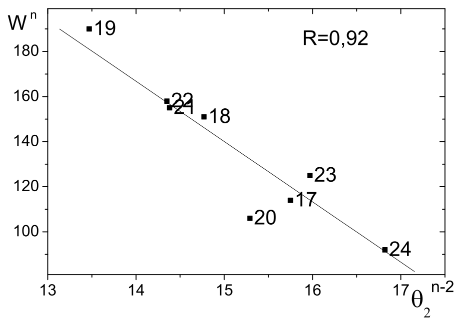

Fig. 6. Amplitude of the nth sunspot cycle (annual sunspot number) as a function of the minimum latitude (in degrees) of ERs in the $(n-2)$th cycle. The solid line shows the linear approximation to the data $W^n = (541.467 \pm 69.939) - (26.761 \pm 4.622) \times \bar{\theta}_2^{n-2}$.

of ERs can be used for a short-term ($dT_1 \sim$ 1–2 years) and a long-term ($dT_2 \sim 1.5$ solar cycles, or 14–17 years) forecast of the amplitude of a sunspot cycle. The appearance of ERs at high latitudes heralding the emergence of sunspots is in agreement with the idea of an extended solar cycle (Wilson et al. 1988) where magnetic activity of the current cycle starts at high latitudes a few years prior to sunspot emergence. In its turn, dT_2 is very close to a time interval to transport surface magnetic field into the dynamo region as required by the transport dynamo models (Choudhuri et al. 1995; Tlatov 1996). The latitude $\bar{\theta}_2$ is lower, when the old cycle activity penetrates to lower latitudes in absence of high-latitude activity of a new cycle. This implies that $\bar{\theta}_2$ is lower, when overlap between the old and new cycles is shorter. Since the orientation of magnetic fields in two consecutive cycles (cycles n and $n+1$) is opposite to each other, longer overlap between cycles will lead to a weakening of a seed field for $(n+2)$ cycle. In addition, a penetration of magnetic field to lower latitudes may allow for a more efficient cancelation of magnetic field of opposite polarity across the solar equator, which in the framework of the Babcock-Leighton model may lead to a more effective transformation of magnetic fields of active regions into poloidal field of future cycles.

Finally, using the found relation between the minimum latitude of ERs and the amplitude of a solar cycle (Fig. 6), we predict a relatively modest cycle 24 with an annual averaged amplitude of about $W = 92 \pm 13$. This prediction is in agreement with the recent forecast for the strength of cycle 24 (92.8 ± 19.6) by Bhatt et al. (2009) based on the geomagnetic aa index.

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