The Astrophysical Journal, 680:1553–1559, 2008 June 20

A CENTURY OF POLAR FACULAE VARIATIONS

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Received 2008 January 25; accepted 2008 March 13

ABSTRACT

The numbers of faculae at the poles of the Sun have been estimated from white-light images obtained at the Mount Wilson Observatory during 1985–2006 and combined with prior estimates extending back to 1906, when the observations began. The combined data show an 11 yr cyclic variation with faculae maxima occurring during sunspot minima in each of the past 10 sunspot cycles. Also, these numbers of polar faculae are well correlated with the line-of-sight component of the polar magnetic field measured at the Wilcox Solar Observatory since 1976. The numbers of polar faculae show a secular decrease since 1986, suggesting that the polar fields are now weaker than they have been during any cycle in the past century.

Subject headings: Sun: corona — Sun: coronal mass ejections (CMEs) — Sun: magnetic fields

1. INTRODUCTION

Polar faculae are visible on white-light images obtained daily at the Mount Wilson Observatory since 1906. Estimates of the numbers of faculae in the vicinity of the north and south poles were summarized for the interval 1906–1964 (Sheeley 1964, 1966), and then updated twice—first through 1975 (Sheeley 1976) and then through 1990 (Sheeley 1991). This paper describes a third update that includes observations through the spring of 2007.

Each study had a different motivation. In 1964, the objective was to see if the polar fields had an 11 yr cyclic variation as predicted by Babcock (1961) and Leighton (1964). The polar faculae did have a cyclic variation, disappearing at sunspot maximum and appearing in large numbers around sunspot minimum. In 1975, the objective was to compare the polar fields during the *Skylab* era of coronal holes and high-speed solar wind streams with the polar fields in earlier cycles (Zirker 1977; Sheeley et al. 1976). After transient bursts in the numbers of polar faculae during 1959–1960, the numbers had been small for several years. However, they increased during 1972–1973 and produced nominal values of about 20 during the 1976 sunspot minimum. In 1990, the objective was to test polar magnetic field measurements and to correlate intermittent changes in the numbers of faculae with the occurrence of episodic poleward surges of flux (Howard & Labonte 1981; Wang et al. 1989). The numbers of polar faculae were well correlated with the line-of-sight fields observed at the Wilcox Solar Observatory (WSO) during 1976–1990 and had values that were 50% larger during the 1986 sunspot minimum than during the prior sunspot minimum in 1976. A sudden increase in the number of south polar faculae in 1974 was associated with a poleward surge of flux from the southern-hemisphere sunspot belt, suggesting that the large transient variations observed earlier in the century may also have been caused by poleward surges of flux. In fact, some decreases in the numbers of polar faculae (like those at the south pole in 1960 and the north pole in 1963) were too rapid to have been produced by supergranular diffusion alone, and seemed to be evidence for large surges of flux from the sunspot belts.

The objective of the present update is to increase the length of the observational sample, so that it spans 100 years and has a greater overlap with modern magnetograph observations. A long time series of self-consistent polar faculae estimates might help to constrain theories of the sunspot cycle (Wang et al. 2002, 2005; Schatten 2005; Svalgaard et al. 2005) and the solar dynamo (Wang et al. 1991; Dikpati & Gilman 2006) and place the variety of current solar and heliospheric observations in perspective. Also, this long time series might help to clarify the issue of how the strength of the interplanetary magnetic field (and therefore the amount of open flux) has evolved during the past 100 years (Lockwood et al. 1999; Lockwood 2001; Svalgaard et al. 2004).

In this paper we focus primarily on the polar faculae measurements themselves, and limit the comparison with other data to a discussion of the most obvious implications. One of these implications is that the polar field is too weak to flatten the streamer belt during the current era of low sunspot activity. This may account for the extended interval of low-latitude coronal holes, solar wind high-speed streams, and recurrent geomagnetic activity. Another implication is that the poleward meridional flow speed in sunspot cycle 23 may be faster than expected for such a weak sunspot cycle.

2. THE MEASUREMENT PROCEDURE

During this third update, the numbers of north and south polar faculae were determined using essentially the same procedure that was used previously. Two sets of 17 cm images were selected for the interval 1985–2006. The south deck consisted of the five best images during the February 15–March 15 interval when the south pole is most visible from Earth. The north deck consisted of the five best images obtained during the August 15–September 15 interval when the north pole is most visible. The selection was based on image quality (atmospheric seeing), photographic contrast, and the (often unsatisfiable) criterion that such high-quality images be uniformly spaced through each 1 month "solar rotation" interval. Also, the 1985–2006 interval was intentionally chosen to overlap with the interval 1976–1990 used in the previous update in 1990 so that 6 years of identical images would be available for a consistency calibration. Finally, because the present update occurred in June, images for the spring interval of 2007 were included.

The counting of polar faculae was a subjective process based on eye estimates of bright features (dark on the negative transparencies) whose contrasts were comparable to those of low-latitude faculae, but whose sizes were much smaller. To remove a possible chronological bias, the spring and fall decks (containing 115 and 110 images, respectively) were each shuffled and the polar faculae were counted before the dates of observation were noted and recorded. The numbers of faculae at each pole were counted for every image. However, the numbers in the unfavorable

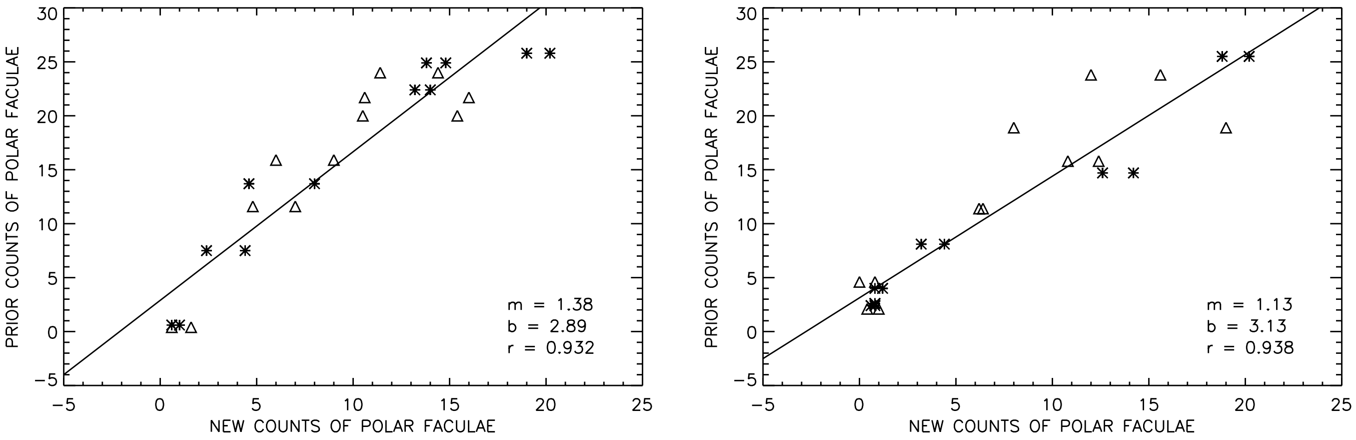

Fig. 1.—*Left*: Comparison between new (2007) and prior (1990) measurements of the numbers of polar faculae for the interval 1985–1990. *Right*: A similar comparison between measurements obtained in 1990 and 1975 for the interval 1971–1975. Triangles and asterisks refer to the north and south pole, respectively. The correlation coefficients (*r*), and vertical intercepts (*b*) of the regression lines are essentially the same, but the slope (*m*) is larger for the more recent comparison.

hemisphere (north in spring and south in the fall) were systematically smaller than those in the favorable hemisphere and are not included in this analysis.

Later, the measurements were reorganized in chronological order, and the averages and standard deviations of the five measurements per year were computed. The entire process of shuffling, counting, reorganizing, and computing was repeated for each deck to test the consistency of the measurement technique. As we shall see later, the repeated measurements fell within the error bars of the original ones (and vice versa). However, for the 1985–1990 overlap interval, both sets of 2007 estimates were systematically and noticeably smaller than the estimates obtained from those same plates in 1990. This discrepancy was a surprise because the first (1975) and second (1990) updates did not show appreciable differences during their overlap intervals. Consequently, a section of this paper is devoted to the cross calibration of the recent and earlier measurements.

As a spot check on measurements obtained prior to 1985, some additional images during 1920–1975 were selected for reexamination. This was an ad hoc procedure, carried out separately from the processing of the main decks for 1985–2006. Images were selected for the spring intervals (1920–1921, 1933–1935, 1942–1945, 1952–1955, 1958–1961, and 1974–1975) and the fall intervals (1940–1943, 1952–1953, 1959, 1962–1963, and 1974). However, these images were not combined into spring and fall decks for individual shuffling and counting. Instead these images were examined in somewhat arbitrary groups as they were encountered: 1920–1921 (spring), 1941 (fall), and 1952 (fall) were shuffled together in the first group; 1942–1943 (spring and fall) and 1940 (fall) in the second group; 1944–1945 (spring), 1953 (fall), and 1953–1955 (spring) in the third group; and 1933–1935 (spring), 1958–1959 (spring), 1959 (fall), 1962–1963 (fall) in the fourth group. Images for 1974 (fall), 1974–1975 (spring), and 1962–1963 (spring) were retrieved from their temporary location at UCLA, and treated separately without shuffling before they were examined. In general, it was more time consuming to examine the older images because they were recorded on glass-backed emulsions with two plates per day often stored in the same envelope. Except for the unshuffled decks, the numbers of faculae were counted and recorded prior to noting and recording the dates of observation. Then, the measurements were sorted chronologically and the averages and standard deviations were calculated.

However, the measurement procedure was not repeated for any of the groups in this ad hoc collection. Because the repeated measurements of the main decks in 1985–2006 (and in all previous intervals) were consistent with the original measurements, it seemed likely that repeated measurements of the ad hoc collection would also be consistent. Consequently, the time was used for examining more of the older plates. As is discussed in the next section, these spot checks in 2007 gave systematically lower values than the estimates made in 1964. Except for the north deck in 1974 and the south deck in 1974–1975 (which required a calibration factor of 1.38), the 2007 estimates of the older plates were lower than the earlier estimates by a factor of 3.

3. CROSS-CALIBRATION WITH EARLIER MEASUREMENTS

The left panel of Figure 1 compares recent estimates of the numbers of polar faculae during 1985–1990 with the estimates obtained for the same plates in 1990. The two sets of 1990 estimates were averaged before plotting (along the vertical axis) against the original and repeated values of the estimates made in 2007 (along the horizontal axis). These data points are fit by a line whose slope (*m*) is 1.38 and vertical intercept (*b*) is 2.89. The correlation coefficient *r* is 0.93, indicating that the 1990 and 2007 measurements of those plates were well correlated.

The slope $m = 1.38$ implies that the new measurements are underestimates that need to be multiplied by 1.38 before plotting them with measurements obtained in 1990 (and by implication in all previous counting sessions). Because this was the first time that such an appreciable calibration shift was encountered, a similar comparison was made for the overlap interval 1971–1975 between the updates in 1990 and 1975. This result is shown in the right panel of Figure 1. The correlation coefficient ($r = 0.94$) and vertical intercept ($b = 3.13$) are essentially the same as the values obtained in the left panel. However, the slope ($m = 1.13$) is lower, showing that the 1990 estimates were only slightly smaller than the ones obtained in 1975 (Sheeley 1991). In this paper, the small calibration shift obtained in 1990 will be neglected, but the larger value of 1.38 will be applied to the measurements for the intervals 1985–2006 (in the north) and 1985–2007 (in the south).

4. RESULTS

Figure 2 shows the resulting plots of the numbers of north and south polar faculae for the past 100 years. The numbers of faculae were estimated at the time of their maximum visibility (fall or spring) during each year and have been assigned the polarity of the associated polar fields (or extrapolated smoothly through

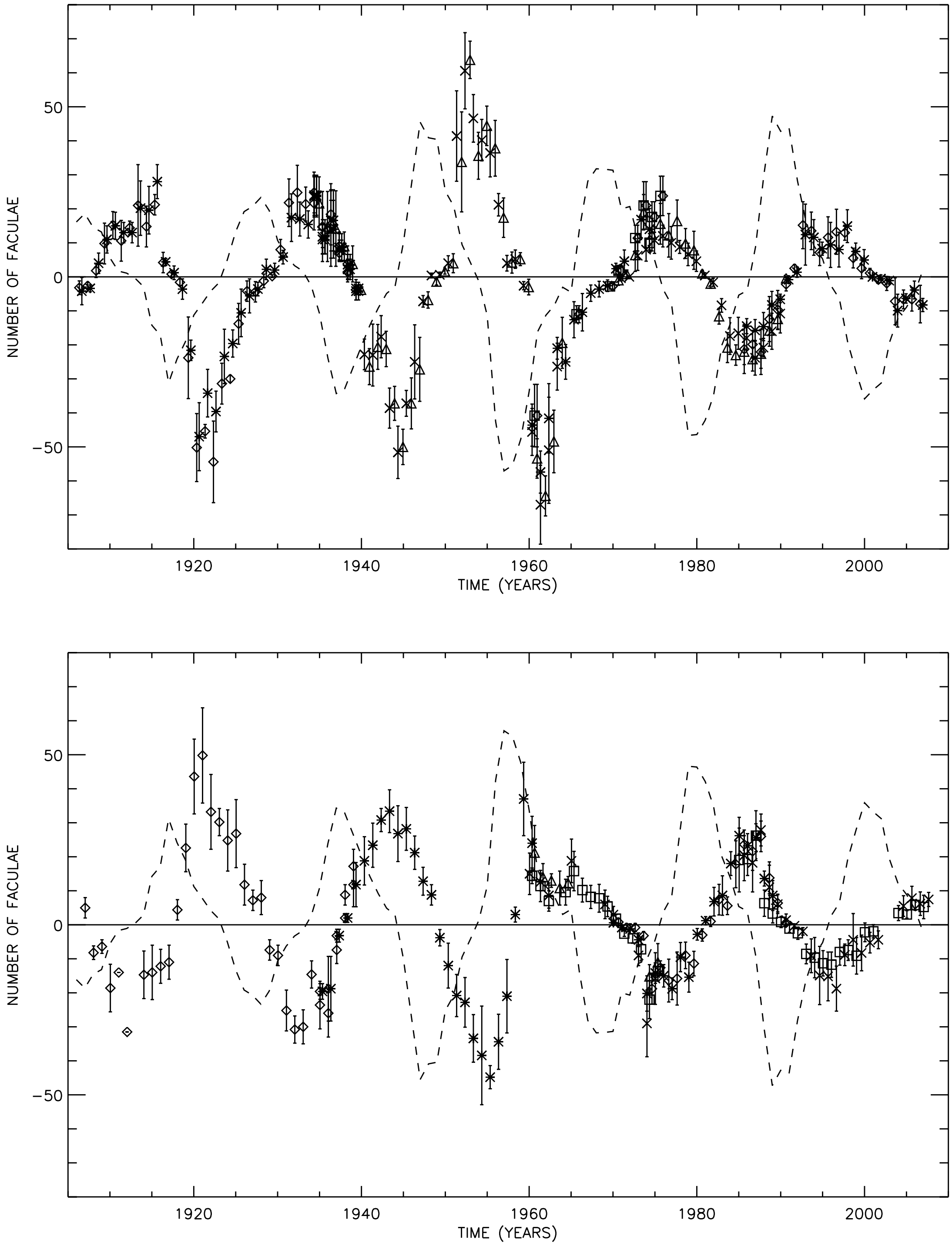

Fig. 2.—Panels show the north (*top*) and south (*bottom*) polar faculae. Signed numbers of polar faculae, at their times of greatest visibility (fall or spring), and the yearly averaged sunspot number, multiplied by 0.3 and assigned the polarity of the following spots in each hemisphere (*dashed lines*). The new counts of polar faculae for 1974–1975 and 1985–2007 have been multiplied by the calibration factor 1.38. Successive temporal strings of data are indicated by diamonds, asterisks, triangles, crosses, and squares.

zero in premagnetograph years). The recent measurements for the interval 1985–2006 (north) and 1985–2007 (south) have been multiplied by the factor 1.38 mentioned above. In each hemisphere, successive temporal strings of data are indicated by diamonds, asterisks, triangles, crosses, and squares, repeated cyclically as necessary to represent all of the measurements. For reasons discussed in the next paragraph, measurements were not available for the spring interval of 2002–2003, which forms a gap in the lower plot. The recent ad hoc measurements of the numbers of faculae during years prior to 1985 have not been included, except for 1974 (north) and 1974–1975 (south), whose values require the same calibration factor of 1.38 that was found for the 1985–1990 estimates. Despite this calibration shift, the recent polar faculae maxima are still weaker than the prior ones in 1996 and 1986. In fact, the peak values at both poles have decreased monotonically since their maxima around 1986.

For comparison, the yearly averaged sunspot number for the full disk has been scaled by a factor of 0.3 and plotted with the polarity of the following sunspots in each hemisphere. This comparison continues to show the 90° phase shift in which the sunspot number

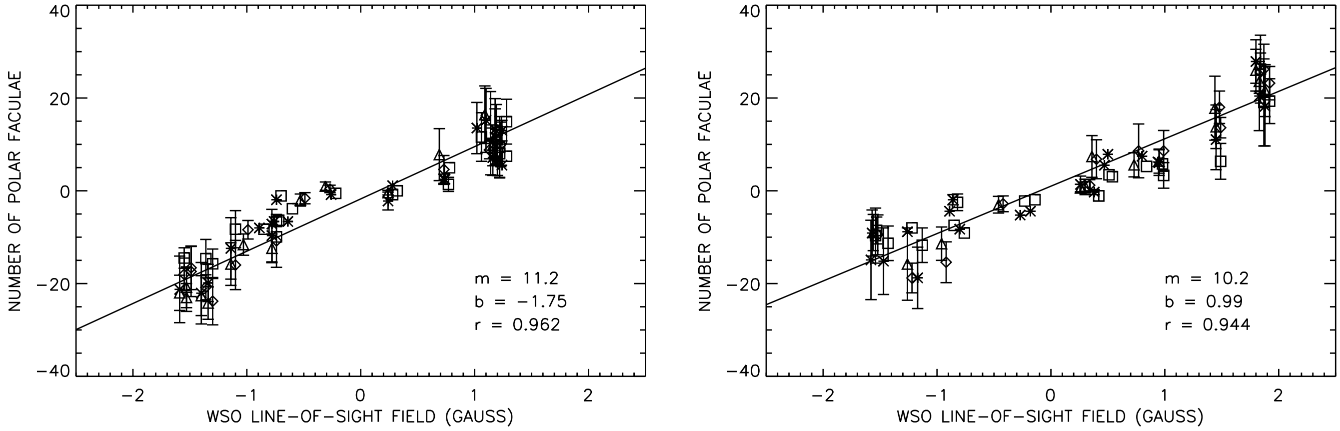

Fig. 3.—Numbers of signed north (*left*) and south (*right*) polar faculae during 1976–2006, plotted vs. the WSO line-of-sight component of polar magnetic field during the same favorable (spring/fall) intervals. Recent polar faculae measurements and their error bars have been multiplied by the calibration factor 1.38. The data string coding is: triangles (1970–1990), diamonds (1970–1989 repeated), asterisks (1985–2006), and squares (1985–2006 repeated).

reached its peak about 5 years before the numbers of polar faculae reached their peaks. However, the present update also shows that the strength of the sunspot cycle is not simply related to the strength of the following cycle of faculae. In particular, the sunspot maxima in 1980 and 1990 had approximately the same strength, but the numbers of polar faculae in 1986 are greater than those in 1996. Also, the numbers obtained during the present sunspot minimum are smaller than the numbers obtained in all previous sunspot minima of the past century. The second lowest set of numbers occurred at the south pole in the mid-1960s for several years after the transient increase in 1959.

During the spring of 2002, the plates were unusable because developer streaks masked any possible polar faculae. The fall plates for 2002 were also of low quality, but were usable. However, beginning in the spring of 2003, the contrast of both the spring and fall plates fell significantly below prior values. Even the equatorial faculae became difficult to see. This low contrast, combined with clouds and poor seeing, made the spring 2003 plates unusable as well. Although the new film had good quality control, its very low contrast gave the impression of a uniformly gray disk with sunspots, but no granules, and faculae that were barely visible. Consequently, the grades that were assigned to the plates since 2002 fell into the C^- (or worse) range compared to the B–C average of the prior plates. This degradation may be responsible for part of the reduction in the numbers of polar faculae that were counted during the present cycle.

Figure 3 compares the signed numbers of north and south polar faculae with the strengths of their associated polar fields measured at the Wilcox Solar Observatory (WSO) during 1976–2006. The recent counts of faculae during 1985–2006 have been multiplied by 1.38 before combining them with the earlier counts. The polar field strengths refer to the same intervals (spring or fall) that the polar faculae were most visible, and were determined by averaging the three measurements that were obtained during each interval.[1] The regression lines fit these data almost equally well, with correlation coefficients of 0.96 (north) and 0.94 (south), and slopes of 11.2 faculae G^{-1} (north) and 10.2 faculae G^{-1} (south). These values are close to the ones obtained during the last update when data for the north and south poles during 1976–1990 were combined to obtain a correlation coefficient of 0.96 and a calibration factor of 11.8 faculae G^{-1} (Sheeley 1991).

The values of 11.2 and 10.2 faculae G^{-1} were used to convert the WSO polar field measurements into equivalent numbers of north and south polar faculae. These numbers are plotted as solid lines in Figure 4 together with the numbers of polar faculae during 1971–2006. These panels show a good agreement between the numbers of faculae and the polar field strength during most of the interval, including the recent years of weak polar field. At the south pole during 2004–2007, the WSO field strength was slightly larger than the equivalent number of polar faculae,

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[1] See http://wso.stanford.edu/Polar.html.

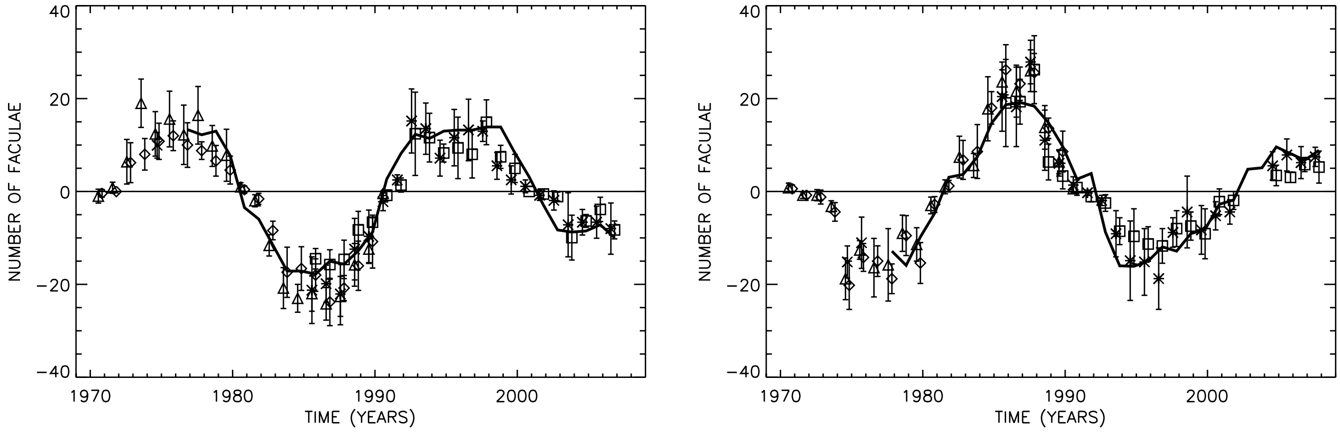

Fig. 4.—Numbers of signed north (*left*) and south (*right*) polar faculae plotted vs. time during the interval 1971–2007 together with the equivalent strength of the WSO line-of-sight polar fields (*solid lines*). The data string coding is the same as in Fig. 3, except that new measurements for 1974 (north) and 1974–1975 (south) are represented by crosses.

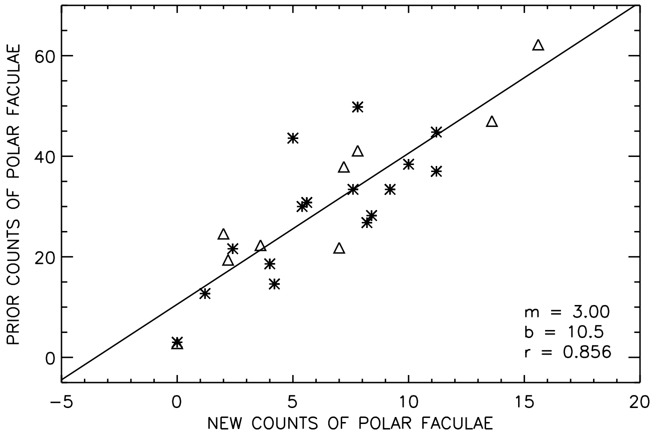

Fig. 5.—Plot similar to those in Fig. 1, but comparing new (2007) and prior (1964) measurements of the numbers of polar faculae for selected years of the interval 1920–1963. The correlation coefficient (*r*) is smaller (0.86) and the calibration factor (*m*) larger (3.0) than the respective values of 0.94 and 1.13–1.38 shown in Fig. 1 for more recent data.

but still within the error bars of those measurements. This increases the likelihood that the secular weakening of the numbers of polar faculae during the past three cycles is real and not just a consequence of the relatively poor quality of the white-light images obtained at Mount Wilson since 2002.

The relatively high degree of correlation between the WSO measurements and the numbers of polar faculae also means that the conversion factors of 11.2 and 10.2 faculae G^{-1} can be used to rescale the plots in Figure 2 so that they show the equivalent line-of-sight polar field strengths in gauss during the favorable intervals (spring and fall) of the past 100 years. We can think of those plots as showing what the WSO measurements would have looked like if they had been started in 1906, instead of late 1975.

It is interesting to compare the recent measurements of the older plates (obtained prior to 1985) with the earlier measurements of those same plates. There were some special cases. Measurements for 1974 (north) and 1974–1975 (south) fell along the same regression line that was obtained for the 1985–1990 interval (shown in Fig. 1, *left*). Consequently, these measurements were included with the recent ones in the plots of Figure 2. Also, there were no pole markers on the plates in 1920 (south), and the plates in 1921 (south) lacked the "dot" that distinguished the north and south poles. A red crayon had been used to indicate the location of the north and south poles on some of the 1920 plates, but those north/south assignments and locations were not confirmed during this third update. Presumably, the south pole was the one that showed the greater number of faculae during those spring intervals. Nevertheless, even those larger values were lower than the ones obtained previously (5.0 in 1920 and 7.8 in 1921, compared to prior values of 43.6 and 49.8 in those years).

Figure 5 compares the recent and prior measurements of these older plates (including the 1920–1921 plates, but excluding the plates in 1974 [north] and 1974–1975 [south]). The correlation coefficient is 0.86, and the corresponding slope of the regression line is 3.0. In this figure, the 1920–1921 points (two asterisks far above the regression line) are the greatest outliers. If they are removed from the comparison, the correlation coefficient increases to 0.92, but the slope remains virtually the same at 3.0. Thus, the recent measurements of the older plates are fairly well correlated with the prior estimates, but are smaller by a factor of approximately 3.0. For completeness, these new measurements of the older plates (excluding 1920–1921) have been multiplied by 3.0 and included with the measurements that are plotted in Figure 2. The result is shown in Figure 6.

The 100 yr plots in Figure 6 look essentially the same as those in Figure 2, except for some occasional thickening of the tracks, caused by the larger error bars of the recent measurements. Notable examples occurred in the south during 1933–1935, 1942–1945, and 1952–1955. Also, the new measurements verified the transient strengthening at the south pole during 1959–1960 and some of the large excursions in the north in 1952–1953. In this figure, the sunspot number was assigned the polarity of the leading sunspots in each hemisphere, rather than the polarity of the trailing spots as was done in Figure 2. This shifted the phase by 180°, and caused the faculae plots to lead the sunspot plots by 90°, consistent with the idea that differential rotation winds up the polar fields to form the toroidal fields of the following cycle (or cycles).

5. SUMMARY AND DISCUSSION

The numbers of north and south polar faculae have been determined at their times of greatest visibility from Earth (spring and fall) during the years 1985–2006, and combined with prior measurements during 1906–1990 to form a sequence that now spans the 100 yr interval 1906–2006. These numbers were assigned the polarities of the associated polar magnetic fields (or extrapolated smoothly through zero in the premagnetograph era prior to 1952) and plotted versus time. For comparison, the yearly averaged sunspot number for the full disk was also assigned a magnetic polarity, which caused the numbers of faculae to lead or lag the sunspot number by 90°, depending on whether the sunspot polarity was taken to be the sign of the leading or following spots in each hemisphere. These plots showed that the current numbers of polar faculae are smaller than those attained during any sunspot minimum since observations began at Mount Wilson in 1906.

The lower quality of the recent MWO white-light images might have caused an underestimate in the measured numbers of polar faculae since 2002, especially at the south pole whose interval of maximum visibility occurs during February–March when the observing conditions are often unfavorable at Mount Wilson. However, the measured decrease was not entirely due to the lower quality of the recent images because these numbers were well correlated with the WSO polar field measurements, which also showed the decrease. Moreover, this decrease is also visible in MWO magnetograms.[2]

One reason for updating the polar faculae measurements was to test the hypothesis that the polar field reversal is maintained by the variation of meridional flow speed from one sunspot cycle to the next (Wang et al. 2002). If the poleward flow were slower, then it ought to permit a greater amount of transequatorial diffusion and annihilation of leading-polarity flux, and produce a greater imbalance of trailing-polarity flux for reversing the polar field in each hemisphere. If the speed were faster, the opposite would happen, and there would be less unbalanced flux for reversing the polar fields. Thus, a low flow speed would increase the efficiency of a weak sunspot cycle, and a high flow speed would decrease the efficiency of a strong cycle. If the speed and cycle strength occurred in this combination, they might maintain the reversal of the polar fields. After simulating cycles 13–22 (1888–1997), Wang et al. (2002) noticed that the best fit was achieved when the fastest speeds occurred in the cycles with anomalous fluctuations in the numbers of polar faculae, as if those cycles contained major surges of flux.

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[2] See http://www.astro.ucla.edu/~ulrich/Big_web_images/Cycle24.pdf.

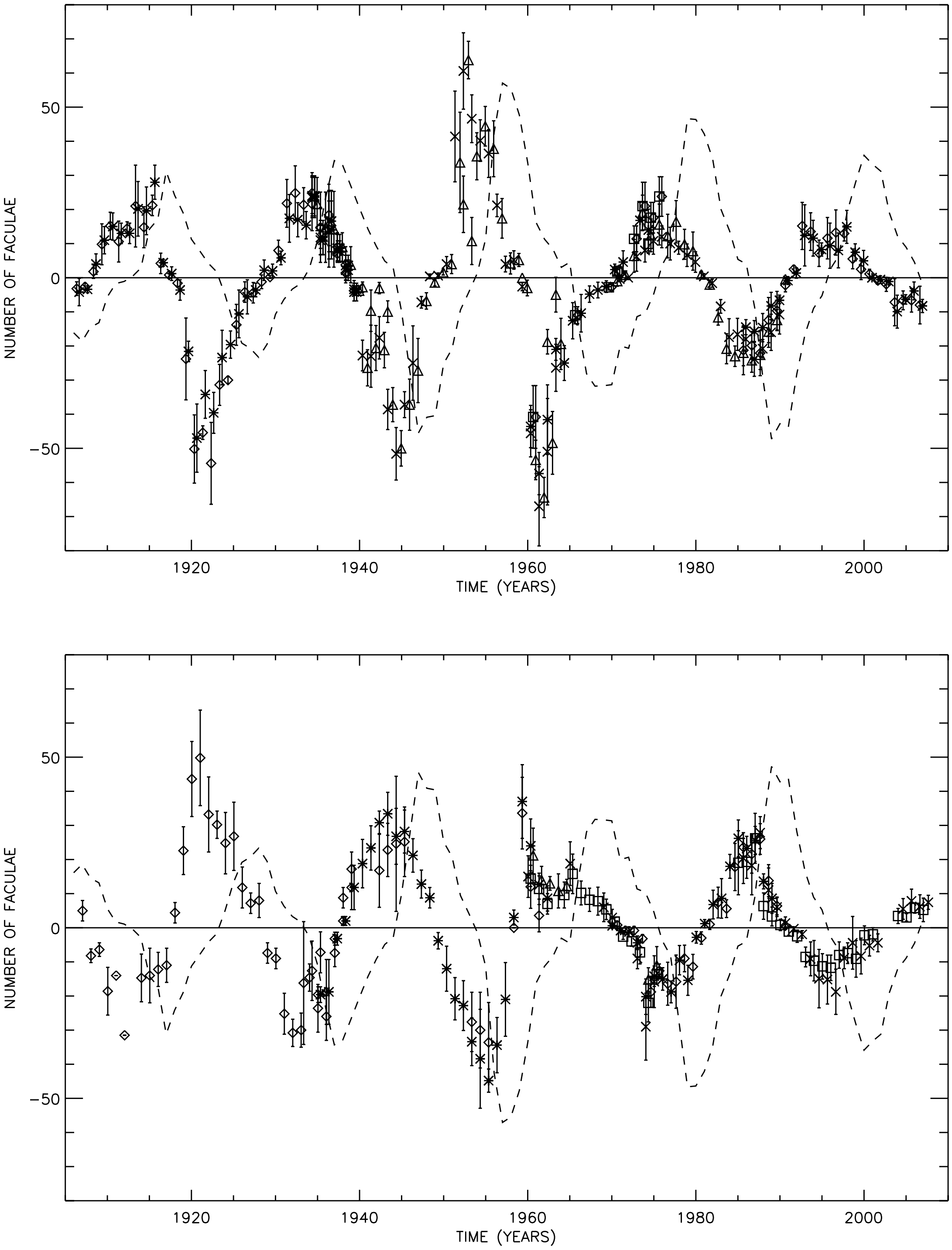

Fig. 6.—Same as Fig. 2, but including recent measurements of selected plates from the interval 1933–1963. Both the values and the rms error estimates of these additional measurements have been multiplied by the calibration factor 3.0, obtained from Fig. 5. Also, the sunspot numbers (*dashed lines*) have been assigned the polarities of the leading sunspots in each hemisphere, rather than the trailing spots as was done in Fig. 2.

The current update does not help to identify poleward surges or determine their speeds during past sunspot cycles when flow speed measurements are unavailable. For that purpose, one might examine time-lapse sequences of white-light images (Sheeley & Warren 2006) or Ca II K-line spectroheliograms.[3]

However, the current update did reveal one new anomaly: Not only were the recent numbers of polar faculae small, as expected from magnetic measurements of the associated polar fields, but these numbers of polar faculae were the smallest of any sunspot minimum in the past 100 years. Sunspot cycle 23 (which peaked during the year 2000) was weaker than cycle 22, and might be expected to provide less trailing-polarity flux for reversing the polar field. However, Figures 2 and 6 show several sunspot cycles (e.g., 14–17 and 20) that were weaker than cycle 23, but were followed by large peaks of polar faculae. This suggests that the weakening of the recent sunspot cycle was not accompanied by an offsetting reduction in meridional flow speed. Supporting this idea, MWO Doppler measurements show an increase in the

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[3] See http://www.astro.ucla.edu/ulrich.

poleward flow speed at least through 2004 (Ulrich & Boyden 2005) and MWO magnetic measurements show the presence of poleward surges through the year 2007 (Y.-M. Wang, private communication).

The present polar field may be so weak that it is not able to flatten the coronal streamer belt. This would account for why the streamer belt is so much more convoluted now than it was at the end of cycle 22 in 1996–1997. Equivalently, in the absence of a strong polar field, relatively weak fields in the sunspot belts might open up to form low-latitude coronal holes. These low-latitude holes and their associated solar wind high-speed streams are responsible for the corotating interactions regions that have dominated observations with the Sun Earth Connection Coronal and Heliospheric Investigation (SECCHI) instruments on the *Solar Terrestrial Relations Observatory* (*STEREO*) spacecraft (Sheeley et al. 2008a, 2008b). In contrast, Figures 2 and 6 show that the numbers of polar faculae were large during most previous sunspot minima. During those times, we would expect historical eclipse observations to show a flat streamer belt confined to the equator and we would expect geomagnetic records to show an end to the recurrent patterns that traditionally occur during the declining phase of the cycle.

Another reason for updating the polar faculae measurements was to provide information for forecasting the strength of future sunspot cycles. This approach is based on the idea that the poloidal field of one sunspot cycle is wound up by differential rotation to produce the toroidal field for the next cycle. One school uses the polar field strength as a measure of this poloidal field and supposes that a weak polar field at one sunspot minimum will lead to a weak sunspot cycle 5 years later (Schatten 2005; Svalgaard et al. 2005). Thus, the present very weak field shown in Figure 6 would be followed by a weak sunspot cycle. Another school supposes that the conversion takes much longer, and concludes that the strength of the next sunspot cycle is determined by contributions from the poloidal fields of more than one prior cycle (Dikpati & Gilman 2006). In this case, the relatively weak polar field during cycle 23 might be less important than the stronger polar fields during cycles 21 and 22 for determining the magnitude of the next sunspot cycle.

Although the new estimates of the numbers of polar faculae during 1920–1963 were fairly well correlated ($r = 0.86$) with the 1964 estimates, the calibration factor increased from approximately 1.0 to 3.0. This calibration shift was probably not due to changes in the measurement environment because the 1990 update was carried out at three different locations (the MWO plate vault, the plate storage area at UCLA, and Mount Wilson) and gave results that were within the error bars of the 1975 update. A more likely explanation is that the criteria for identifying and counting faculae changed in the four decades since the first counting. By comparison, the original and repeated measurements in 1964 (and in every subsequent update) were performed in quick succession, which did not allow time for the criteria to change. This would explain why the original and repeated measurements always agreed within the error bars. On the other hand, the 6 month interval during 1963–1964 was long compared to the 3 day intervals that were typically used for each of the updates. This means that more time was used for examining the older plates, and a higher quality result may have been obtained.

I am grateful to R. K. Ulrich (UCLA) for permission to examine this historical collection of white-light images, and to A. Phifer (CIW) and his colleagues for hospitality at the Santa Barbara Street office of the Carnegie Institution of Washington Observatories in Pasadena where the plates are still kept. J. E. Boyden and S. Padilla helped me to find many of the ~350 images and did most of the work resorting them into chronological order and replacing them in the files. Their efforts gave me time to examine some of the older plates which I had not seen since 1964, and I am especially grateful to John and Steve for making this possible. It is a pleasure to acknowledge useful discussions with Y.-M. Wang (NRL) who suggested that the weak polar fields during the present cycle may be responsible for the convoluted streamer belt and its associated coronal holes. Also, R. K. Ulrich, R. Howe (NSO), I. Gonzalez-Hernandez (NSO), and T. Duvall (Stanford) provided useful comments about meridional flow speed measurements. Finally, I am grateful to the referee, whose thoughtful comments led to a substantial improvement of the manuscript. Financial support was obtained from NASA and the Office of Naval Research.

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