A Remarkably Accurate Predictor of Sunspot Cycle Amplitude.

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Abstract

The area ratios of sunspots to white light faculae in the first two years of sunspot cycles 12-21 correlate remarkably well with the peak amplitudes of those cycles between 1878-1980 (Brown and Evans, 1980). This finding could not be used to predict subsequent cycle amplitudes because the Royal Greenwich Observatory program of facular area measurements was discontinued in 1976. We use continuum images from the Michelson Doppler Imager (MDI) and the Heliospheric and Magnetic Imager (HMI) to show that the close relation holds also for cycle 24, and we predict an amplitude of approximately 185 for the current cycle 25.

1. Introduction

Predictions of the amplitude of the next sunspot cycle represent one of the most important practical applications of solar research and indeed, of astronomy. The dynamics of the magnetic cycle is still too uncertain to provide a physical basis for reliable predictions so estimates of the cycle amplitude and timing are still based largely on empirical or semi-empirical models (e.g Schatten, 2005; Svalgaard, Cliver and Kamide, 2005; McIntosh et al, 2020; see e.g. Pesnell, 2020 for a recent review).

Our approach in this study builds on the finding (Brown and Evans, 1980) that the area ratio of sunspot and white light faculae early in a cycle is closely related to the cycle's peak amplitude. This relationship was originally discovered in analysis of the daily measurements of spots and faculae made by the Royal Greenwich Observatory (RGO) between 1874 and 1976. It reproduced to remarkable fidelity the peak amplitudes of the ten cycles 12 to 21.

Unfortunately, the RGO program (Royal Observatory, 1973) ended in 1976 and the areas of white light faculae were no longer measured. This explains why this relationship has not been used to predict cycle amplitudes since its discovery in 1980. Our previous attempts to continue such measurements using the daily Mt Wilson "direct" (i.e. continuum) spectroheliograms were unsuccessful. Limb darkening removal adequate for reliable measurement of facular areas was not possible because of difficulties with emulsion inhomogeneity and plate exposure.

More recently, excellent daily full disk continuum images became available first from the Michelson Doppler Imager (MDI) on the Solar and Heliospheric Observatory (SOHO) beginning in 2001 (Scherrer et al., 1995) and then from the Heliospheric and Magnetic Imager (HMI) on the Solar Dynamics Observatory (SDO) since 2011 (Scherrer et al., 2012). These data enabled us to extend the relationship to cycle 24 and to make a prediction for the present cycle 25.

2. Data analysis

The MDI images were obtained in narrow - band (94 mÅ) quasi-continuum in the wing of the Ni 6768 Å line. The 75 mÅ HMI continuum passband was located in the wing of the Fe I 6173 Å line. Both data sets had been corrected for limb darkening by the P.I. teams. These passbands showed faculae only nearer the limb than a heliocentric angle of approximately 50 degrees, in agreement with their appearance on the continuum spectroheliograms used in the RGO measurements. The resolution, uniformity, and dynamic range of the space-borne imagery (which shows the photospheric granulation) are superior to the definition of the photographic plates used by RGO. A representative HMI image is shown in Figure 1.

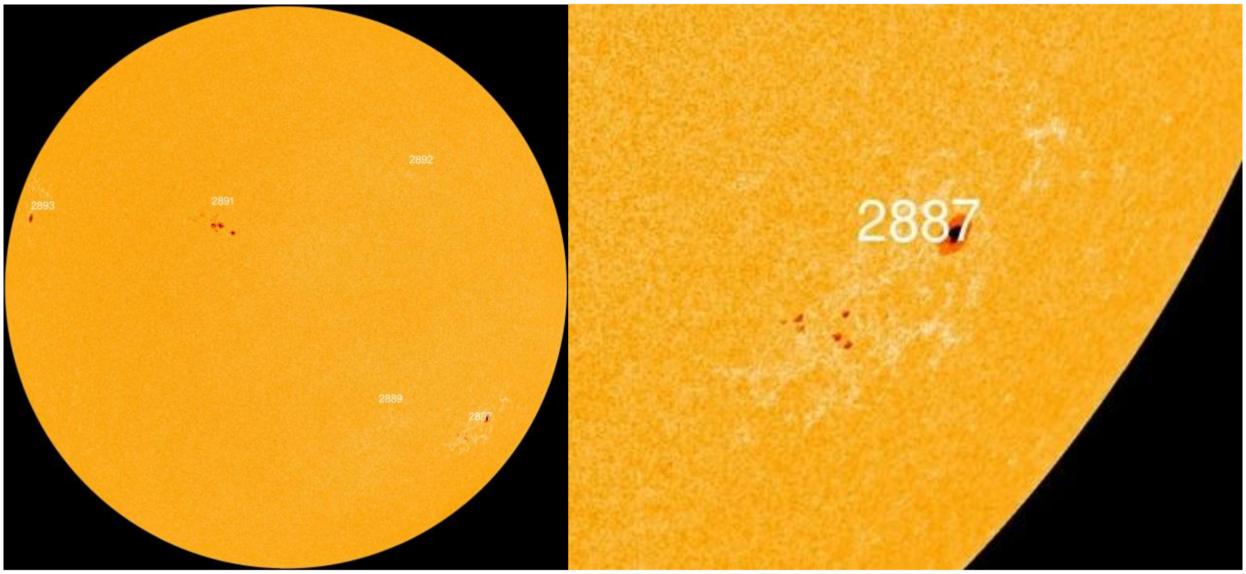


Figure 1 Full disk HMI continuum image (left) and close-up of limb faculae (right) on 1 November 2011.

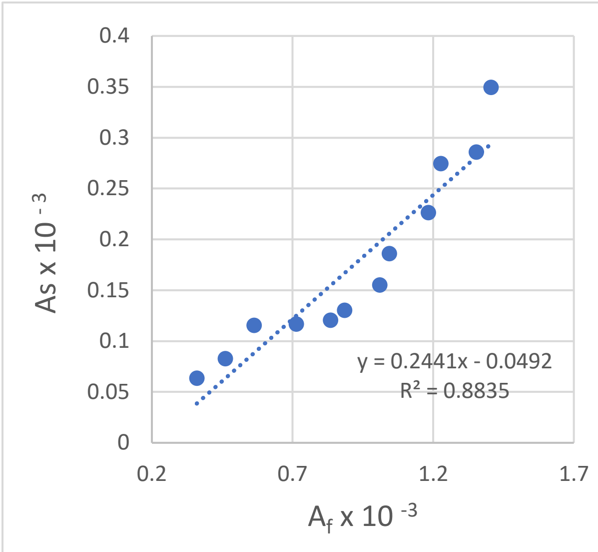
We downloaded and printed four MDI images equally spaced within each of the 24 months for the two first years 2009-2010 of cycle 24 and the same using 2020-2021 HMI data, for cycle 25. The projected areas of spots and faculae on the 130 mm (MDI) and 190 mm (HMI) diameter printed images were measured by counting squares using a magnifier with a reticle grid of 0.5 mm spacing, and corrected for foreshortening. This is essentially the same procedure used by the RGO between 1874-1976. Monthly means of these corrected spot and facular areas were then smoothed with an evenly weighted 13-month running mean.

3. Results and Errors

A plot of these running means of spot (A_s), and facular (A_f) areas for cycle 24 is shown in Figure 2. We see that the spot and facular areas are linearly related (R^2 = 0.88) with a slope of 0.24 in this cycle. A similar plot is shown in Figure 3 for cycle 25. Again, the relation is linear (R^2 = 0.97) but the slope of 0.61 is greater. Brown and Evans (1980) showed that such a linear relationship was characteristic of approximately the first two years of the cycles that they were able to study.

The linear relationship (R^2 = 0.95) between the slopes of the cycles 12-20 and 24, and the peak 13 -month smoothed sunspot number, R_m-max, of that cycle is shown in Figure 4. (Brown and Evans, 1980 do not give the slope value they estimated from incomplete data for cycle 21; they only gave the estimated value of R_m-max for that cycle.) Our slope of 0.24 for cycle 24 falls at the bottom of the plot, corresponding to a peak cycle amplitude of approximately 110. This corresponds closely to its observed 13- month smoothed amplitude of 115. Using the same relationship, the slope of 0.61 measured from our 2020-2021 data for cycle 25 corresponds to a predicted peak amplitude of R_m – max ~ 185.

The values of R_m – max used in Figure 4 and throughout this study are on the re-calibrated International Sunspot Number scale (Clette et al., 2016). These values are about 35% higher than those on the earlier Zurich sunspot number scale used by Brown and Evans (1980).



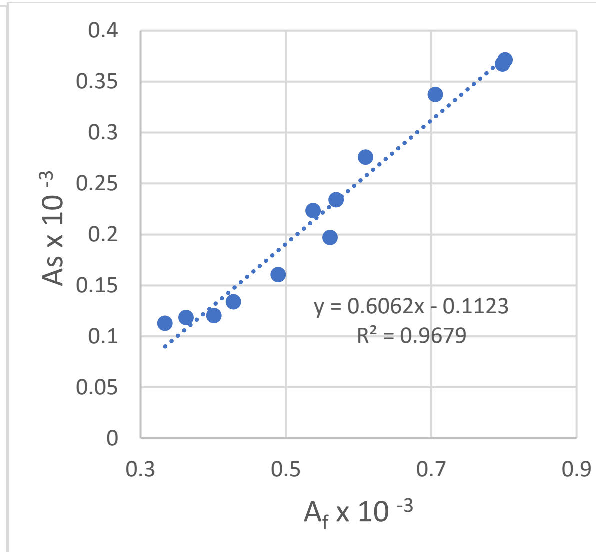


Figure 2 A_s versus A_f for 2009 – 2010; Figure 3 As versus Af for 2020 – 2021.

The slopes of the plots in Figures 2 and 3, and therefore the intersections of the cycle 24 and 25 estimates with the linear fit in Figure 4 could be influenced by possible systematic differences between spot and facular areas measured with MDI and by RGO. Comparison of spot areas over the overlap period between MDI and HMI between August and December 2020 shows a linear relation at 95% confidence with no significant y-intercept, between those two data sets. This agreement supports the earlier finding (Foukal, 2014) that large systematic differences (e.g. Baranyi, Kiraly and Coffey, 2013) occur mainly between data sets reduced using quite different techniques.

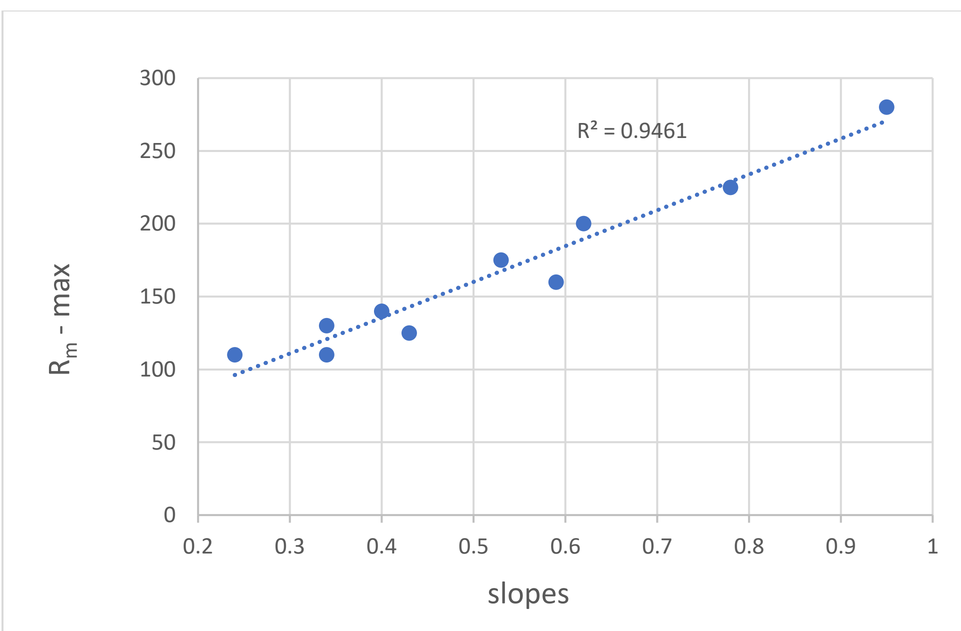


Figure 4. R_m-max versus slopes dA_s/dA_f for cycles 12-20, and 24.

No calibration of MDI versus RGO facular areas is available. But even if a zero-point offset were to exist between RGO and MDI data it would not affect our estimate of the amplitudes of cycle 24 and 25 which depends only on the *slope* dAs/dAf, not on the y-intercept.

Sampling noise due to the 7-day spacing of the images might also contribute to the scatter in Figures 2 and 3, since it is comparable to the lifetimes of spots and faculae and to the time scale of their rotation through the range of facular visibility (Brown and Evans used monthly means of daily RGO data). Finally, inter- cycle variability in the emergence and transport of photospheric magnetic fields (Sheeley, 1992) might also be expected to contribute (Foukal,1998).

4. Discussion and Conclusions

The success of this technique in reproducing the amplitudes of cycles 12-21 and 24 is remarkable. No other technique has demonstrated comparable accuracy over as long a time scale. The prediction of R_m – max ~ 150 by Brown and Evans (1980) for a tenth cycle (21) also turned out to be correct. But the technique provides only 2-3 years advance notice of future solar activity, so it cannot supplant methods that provide longer advance times. Nor does it predict when the next maximum will occur, although a useful relation between R_m-max and the cycle rise time (Waldmeier, 1978) can be helpful in this respect. Comparison of our prediction for cycle 25 with forthcoming observations will further test whether it can be expected to provide more reliable, even if less early, information on the amplitude and timing of future cycles.

The amplitude of cycle 25 predicted here is greater than the value of approximately 120 published by the International Prediction Panel (IPP) in 2019. Judging by the rapid rise of activity in this cycle, it is likely to be more accurate (see https://www.swpc.noaa.gov/products/solar-cycle-progression for a comparison of the IPP prediction with current solar activity). This technique could not have been used by the IPP in 2019 even if the possibility of obtaining facular areas after 1976 had been recognized because data from the first two years of the cycle are required, but a revised prediction would have been possible by late 2021.

The method described here is empirical but its physical basis can be understood in terms of the factors that determine the relative areas of spots and faculae in the Sun and other late type stars (e.g. Foukal, 1994; 1998). Dark spots are produced by magnetic flux tubes whose cross- sectional areas lie at the upper end of the photospheric flux tube size spectrum. The bright white light faculae lie at the lowest end of that spectrum (Spruit, 1976).

The increase in the slope dA_s/dA_f between cycle 24 and 25, seen in Figure 2, therefore corresponds to a shift in the size spectrum of photospheric magnetic fields towards more power at the larger (sunspot) scales, as the peak amplitude of the cycle increases. Such a tendency of dynamos to shift their power towards lower spatial wavenumbers as their magnetic flux output increases has long been recognized in the observations of very large spots on late-type stars more active than the Sun (e.g. Radick, Lockwood and Baliunas, 1990). It has also been reported in dynamo calculations based on toroidal geometries (e.g. Miesch, 2017)).

The relationship studied here between A_s and A_f does not hold as well between sunspots and chromospheric plages (Foukal, 1998) because the bright plages, observed most commonly in narrow band Ca II K radiation, cover essentially all photospheric magnetic structures except the largest sunspots. So their total area includes not only the most slender flux tubes observed as white light faculae, but also the intermediate size range of photospheric magnetic fields including pores and small spots. This degraded discrimination in scale of structures decreases the sensitivity of the present diagnostic to the shift in this size spectrum with increasing solar activity. So the daily Ca K plage areas available for the cycles 22-23 unfortunately cannot be used to substitute the missing facular areas for those cycles.

Acknowledgements

This study was greatly facilitated by the convenient availability of the daily MDI and HMI images obtained by the Stanford University and Lockheed Corporation Solar Groups, on the Spaceweather.com website. I am grateful to Frédéric Clette for information on the SC 25 Panel prediction of the current cycle, to Leif Svalgaard for drawing my attention to Waldmeier's rule and to Neil Sheeley for comments on the paper. I thank Tom Williams for drawing my attention to the Spaceweather.com site and Jack Martin for facilitating access to the RGO archive at Cambridge University.

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