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Geomagnetic activity indicates large amplitude for sunspot cycle 24

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[1] The level of geomagnetic activity near the time of solar activity minimum has been shown to be a reliable indicator for the amplitude of the following solar activity maximum. The geomagnetic activity index *aa* can be split into two components: one associated with solar flares, prominence eruptions, and coronal mass ejections which follows the solar activity cycle and a second component associated with recurrent high speed solar wind streams which is out of phase with the solar activity cycle. This second component often peaks before solar activity minimum and has been one of the most reliable indicators for the amplitude of the following maximum. The size of the recent maximum in this second component indicates that solar activity cycle 24 will be much higher than average – similar in size to cycles 21 and 22 with a peak smoothed sunspot number of 160 ± 25.

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1. Introduction

[2] Knowing the level of solar activity years in advance has important consequences. High levels of solar activity can heat and inflate the Earth's outer atmosphere. This increases the drag on satellites in low Earth orbit and can lead to their early reentry. Placing a satellite in a low orbit can lead to a costly early end of its mission. Placing a satellite in a higher orbit either increases the launch costs or decreases the payload weight. Accurate and reliable predictions for solar activity levels are needed by the people, companies, and organizations that build, operate, and use satellites.

[3] Geomagnetic activity near the time of sunspot cycle minimum has been shown to be a good indicator for the level of maximum activity during the following cycle. *Ohl* [1966] noted that the geomagnetic index *aa* reaches a minimum near (but usually after) the time of solar activity minimum and that this minimum in the *aa* index is well correlated with the amplitude of the following activity maximum. *Feynman* [1982] suggested that the geomagnetic activity indicated by the index *aa* could be split into two components – one in phase and proportional to the solar activity cycle and a second (residual) component associated with interplanetary disturbances that is out of phase with the activity cycle. This second, interplanetary component often peaks just before solar activity minimum and has been shown to be an even better indicator for the amplitude of the following cycle [*Hathaway et al.*, 1999]. *Thompson* [1993] noted that the number of geomagnetically disturbed days during a cycle (as indicated by the number of days with Ap index $\geq$25 between solar activity minima) is proportional to the sum of the amplitudes of that cycle and the following cycle. While this method for predicting the amplitude of the next cycle requires waiting until cycle minimum occurs, it is also found to be a very reliable method [*Hathaway et al.*, 1999]. All three of these geomagnetic precursor methods indicated a larger than achieved cycle for cycle 23 (Ohl - 135 ± 35; Feynman - 154 ± 25; Thompson - 153 ± 35; achieved - 121) but with the predictions within or just outside the 2σ errors.

[4] The use of geomagnetic activity as a predictor for future solar activity seems counter-intuitive. The Sun is the source of the solar wind disturbances that drive geomagnetic activity and thus it would seem that solar activity should predict geomagnetic activity, not the other way around. Nonetheless, geomagnetic activity near the time of solar activity minimum has proved to be a reliable predictor for future solar activity. A likely explanation for this connection comes from the sources of geomagnetic activity. Solar eruptions such as flares, filament eruptions and coronal mass ejections are active producers of geomagnetic activity. The frequency of these eruptions rises and falls with the solar activity cycle as indicated by the number of sunspots. These eruptions represent the solar cycle component of geomagnetic activity as described by *Feynman* [1982]. Additional drivers of geomagnetic activity include interplanetary shocks from high-speed solar wind streams associated with coronal holes that are out of phase with the sunspot cycle [cf. *Luhmann et al.*, 2002]. As the polar coronal holes expand during the approach to sunspot minimum their low-latitude extensions produce recurrent high-speed streams that give rise to geomagnetic activity. The magnetic field strengths and configurations that give rise to these coronal structures may provide a prelude to the strength of the ensuing sunspot cycle.

[5] Models for the Sun's magnetic dynamo may help to explain this connection. Recent models [cf. *Dikpati and Charbonneau*, 1999] incorporate the Sun's meridional circulation to transport strong, sunspot forming, magnetic field toward the equator at the base of the convection zone. This provides a simple explanation for the equatorward drift of the sunspot latitudes. It also suggests that evidence of the next cycle might be seen in the mid-latitudes prior to the appearance of sunspots. This "extended" solar cycle was suggested earlier by *Wilson et al.* [1988] based on observations of ephemeral active regions, coronal emission-line structures, and the torsional oscillation signal. These structures appear at mid-latitudes prior to the first appearance of the sunspots of the new cycle and may very well contribute to geomagnetic activity at that time.

[6] Predictions for the size for cycle 24 have already been published. *Hathaway and Wilson* [2004] predicted a large

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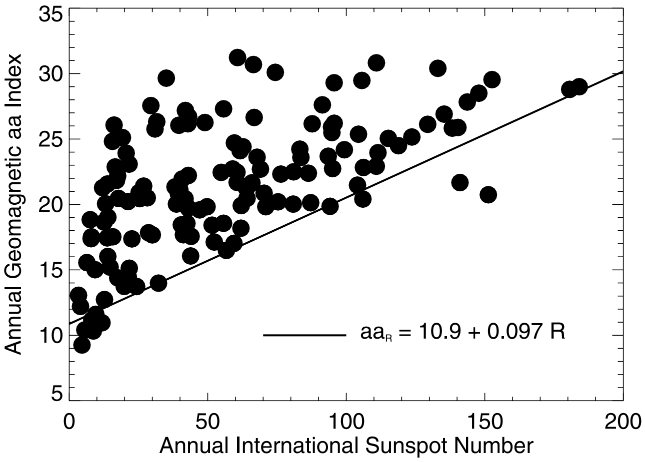

Figure 1. Annual values for the geomagnetic index *aa* as a function of the corresponding annual International Sunspot Number for the years 1868 to 2005. Both monthly activity indices are smoothed with a 24-month FWHM Gaussian and then sampled at yearly intervals. At a given sunspot number there is a baseline level of geomagnetic activity which is proportional to the sunspot number. Geomagnetic activity extends above this level – particularly late in each solar cycle. This baseline level, aa_R, is determined by fitting a line through the lower boundary of activity.

amplitude (145 ± 30 for the maximum of the smoothed monthly sunspot number) for cycle 24 based on the equatorward drift rate of the active latitudes during cycle 22. *Svalgaard et al.* [2005] predicted a small amplitude (75 ± 8) based on the weak polar fields observed on the Sun during the decline of sunspot cycle 23. A significant new development in predicting the solar activity cycle is the use of a dynamo model with assimilated sunspot data as described by *Dikpati et al.* [2006]. Using historical records for sunspot areas and positions over the last 130 years as input for the source of the surface magnetic fields that seed the dynamo, they predict an amplitude of 150–180 for cycle 24.

[7] In this letter we examine recent geomagnetic activity using the methods described by *Feynman* [1982] and find that this activity indicates a much larger than average cycle for solar cycle 24 – on par with the prediction of *Hathaway and Wilson* [2004] and *Dikpati et al.* [2006].

2. Data and Methodology

[8] Geomagnetic activity is measured by noting the rapid changes in the geomagnetic field strength and direction. Numerous observatories have made these measurements and a number of indices have been constructed to characterize the level of activity. The most widely used long-term index is the *aa* index. This index is produced using two observatories at nearly antipodal positions on the Earth's surface. The index is computed from the weighted average of the amplitude of the field variations at the two sites over three-hour intervals. Monthly averages of this index began in January of 1868 with Greenwich, England and Melbourne, Australia as the two sites. Greenwich was replaced by Abinger, England in 1926 and by Hartland, England in 1957. Melbourne was replaced by Toolangui, Australia in 1920 and by Canberra, Australia in 1980. *Svalgaard et al.* [2004] have reconstructed the *aa* index and found that values prior to 1957 should be increased by about 3 nT. We find that this simple correction reduces the scatter in our results and have chosen to include it in the following analysis.

[9] The relationships between the *aa* index and sunspot number are more easily examined when both datasets are smoothed to minimize the short-term variations. A commonly used smoothing function is the 13-month running mean which is implemented as an average with half-weights for the first and last months. *Hathaway et al.* [1999] noted that this filtering still allows for significant high-frequency variations and suggested a Gaussian-shaped weighting function with a FWHM of about 24 months. Smoothing both the monthly *aa* index and the monthly International Sunspot Number with this 24-month Gaussian filter and sampling at yearly intervals reveals the relationship shown in Figure 1.

[10] *Feynman* [1982] had noted that as the sunspot number increases the base level of geomagnetic activity increases as well – this represents a level of geomagnetic activity which is proportional to the sunspot number. Our approach in characterizing this relationship is to find the minimum annual *aa* index in 20 bins in sunspot number (0–10, 10–20, ...190–200) and then find the least-squares fit for a line through these points. The resulting fit is given by the solid line in Figure 1 and the equation relating aa_R, the solar activity cycle component of geomagnetic activity, to the International Sunspot number, *R*.

[11] Following *Feynman* [1982], the "Interplanetary" component of geomagnetic activity, aa_I, is simply given by the residual activity found when the solar cycle component is removed. These two components are plotted together as functions of time in Figure 2. The solar cycle component shows the sequence of sunspot cycle amplitudes for the last 13 cycles. The interplanetary component shows a

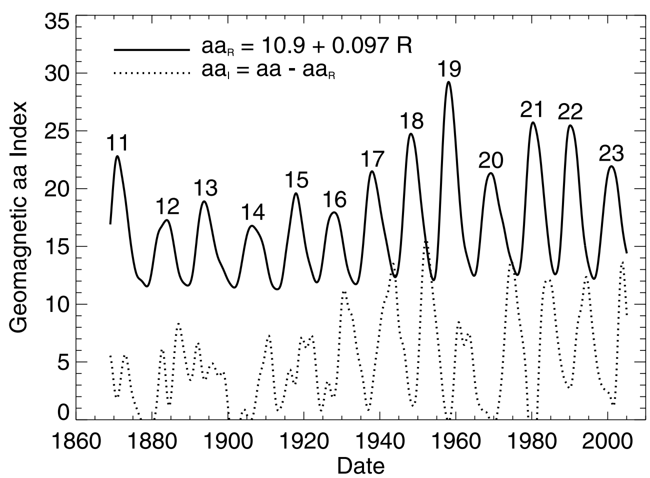

Figure 2. Solar cycle, aa_R, and interplanetary, aa_I, components of geomagnetic activity as functions of time. The solar cycle component is directly proportional to the sunspot number and illustrates the sequence of cycle amplitudes for the last 13 solar cycles (numbered). The interplanetary component has a similar sequence of peaks but they occur several years earlier – usually before the time of cycle minimum.

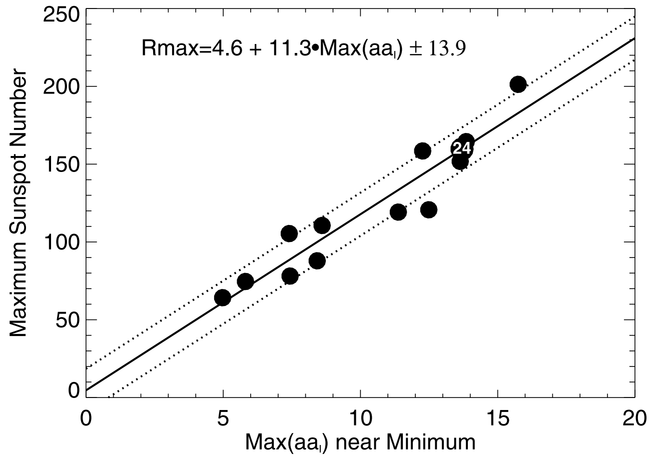

Figure 3. Maximum sunspot number for the following cycle as a function of the maximum in the interplanetary component of the *aa* index. The following cycle amplitude is well correlated with the earlier peak in aa_I with little scatter about a linear relationship (solid line with 1-sigma limits shown with dotted lines). The prediction for sunspot cycle 24 is shown with the circled number 24 – a maximum sunspot number of 160 ± 25.

similar sequence of peaks but shifted back in time – usually to before sunspot cycle minimum. It is this behavior of the interplanetary component that provides predictive capability.

[12] The relationship between the peaks in the interplanetary component of the *aa* index and the amplitude of the following sunspot cycle is shown in Figure 3. There is a strong positive correlation (correlation coefficient 0.94) between the two quantities and the chance of getting this relationship from uncorrelated quantities is less than about 0.1%.

[13] The relationship shown in Figure 3 can be used to predict the size of the next solar cycle. The smoothed interplanetary component of the *aa* index peaked at a level of 13.7 in October of 2003. This indicates a maximum sunspot number of about 160 for sunspot cycle 24. This is similar to the amplitudes of cycles 21 and 22 but less than that of cycle 19. The 90% prediction interval is 160 ± 25; therefore, there is only a 5% chance that cycle 24 maximum amplitude will be smaller than 135.

3. Conclusions

[14] The geomagnetic index *aa* can be split into two components – one proportional to, and in phase with, the sunspot number and another, interplanetary, component aa_I which is out of phase with the sunspot cycle. This second component has peaks in activity that mimic those seen in the sunspot number but shifted in time several years earlier. These peaks in aa_I usually occur before the time of sunspot cycle minimum and provide an accurate prediction for the amplitude of the following sunspot cycle. The recent (October 2003) peak in aa_I indicates a sunspot number maximum for cycle 24 of about 160 ± 14. This prediction is very much in line with the predictions of a large cycle 24 by *Hathaway and Wilson* [2004] and by *Dikpati et al.* [2006] but in contrast to the prediction of a small cycle 24 by *Svalgaard et al.* [2005].

[15] All four of these predictions are based on different methods. The prediction of a small cycle 24 by *Svalgaard et al.* [2005] is based on a correlation observed between directly measured polar fields and sunspot number for the last three cycles, following the method of *Schatten et al.* [1978]. The *Dikpati et al.* [2006] prediction is on the firmest physical ground – a dynamo model based on our current knowledge of the dynamics of the Sun's convection zone (note, however, comments by *Tobais et al.* [2006]). All three of the high predictions are consistent with each other and are based on data from the last 12–13 sunspot cycles. The *Dikpati et al.* [2006] prediction is based on a dynamo model with observational data on sunspot areas and positions. The *Hathaway and Wilson* [2004] prediction is based on an observed, significant but loose, relationship between the equatorward drift rate of the active latitudes and future solar activity. The prediction presented in this letter is based on an observed, significant and tight, relationship between geomagnetic activity and future solar activity. The consistent results with these three methods strongly suggests that cycle 24 will indeed be a large cycle.

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