PERGAMON

Journal of Atmospheric and Solar-Terrestrial Physics 64 (2002) 47–53

Journal of
ATMOSPHERIC AND
SOLAR-TERRESTRIAL
PHYSICS

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The semiannual variation of geomagnetic activity: phases and profiles for 130 years of *aa* data

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Received 2 March 2001; received in revised form 24 September 2001; accepted 17 October 2001

Abstract

We determined the phases of the maxima (spring, fall) and minima (summer, winter) in the curve of smoothed daily averages of the *aa* geomagnetic index, available from 1868 to 1998. The dates we obtained are consistent with the equinoctial hypothesis which has aberration-adjusted theoretical maxima, for a ~440 km s^{-1} (modern epoch) average solar wind speed, on 25 March (experimentally determined to be 27 March, with an uncertainty of ±2 days) and 27 September (27 September) and minima on 25 June (26 June) and 26 December (27 December). We also show that the overall shape of the 30-day smoothed modulation curve throughout the year (broad minima, narrow peaks) bears greater fidelity ($|r| = 0.96$) to the aberration-shifted solar declination δ (the controlling angle, on average, for the seasonal variation under the equinoctial hypothesis) than to the solar B_0 angle ($r = 0.76$; axial hypothesis) or the solar P angle ($r = 0.86$; Russell–McPherron effect). Lastly, a three-parameter fit of the smoothed annual variation of the *aa* data with a function consisting of the sum of the smoothed yearly curves for the δ, B_0, and P angles yielded an amplitude of 0.58 ± 0.07 for the δ component vs. 0.16 ± 0.03 for B_0 and 0.20 ± 0.04 for P. Thus, the phases and profiles of the 6-month wave in the long-running mid-latitude *aa* range index are consistent with control by a dominant equinoctial mechanism. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Geomagnetic activity; Semiannual variation; Equinoctial hypothesis

1. Introduction

The semiannual modulation of mid-latitude geomagnetic range indices such as *ap*, *am*, and *aa* is generally attributed to one or more of three mechanisms: axial (Cortie, 1912; Bohlin, 1977), equinoctial (Bartels, 1925, 1932; McIntosh, 1959; Svalgaard, 1977), and Russell and McPherron (1973). Of these, the Russell–McPherron effect, which predicts a 6-month wave in the B_S component of the solar wind magnetic field in Geocentric Solar Magnetospheric (GSM) coordinates, is commonly accepted as the principal cause of the seasonal variation of geomagnetic activity (e.g., Orlando et al., 1993, 1995; McPherron, 1995; Siscoe and Crooker, 1996). A seasonal variation of solar wind speed resulting from Earth's movement to high solar latitudes in March and September (an axial effect) is often invoked (e.g., Murayama, 1974) as a secondary contributing cause.

Over the years, however, a number of studies have pointed out that the amplitude of the Russell–McPherron (RM) effect is too small (by about a factor of four) to account for the seasonal variation in average values of geomagnetic indices, and/or that the predicted universal time variation does not agree with the observations (Mayaud, 1974a; Berthelier, 1976; Svalgaard, 1977; Schreiber, 1981). Lately, Cliver et al. (2000, 2001) have taken up this theme and have argued as others had previously that the equinoctial effect was dominant. Following Crooker and Siscoe (1986), they suggested that the B_S coupling (i.e., reconnection) efficiency between the solar wind and the magnetosphere was

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PII: S1364-6826(01)00093-1

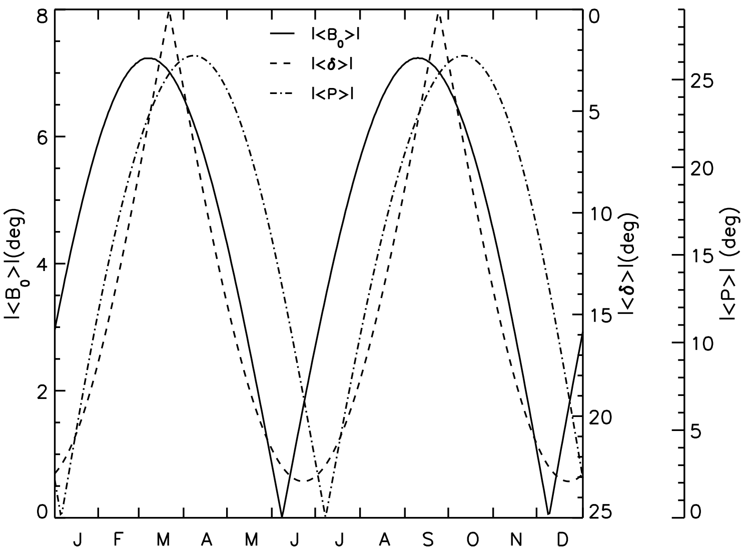

Fig. 1. Annual variations of the absolute value of: (1) the solar B_0 angle (axial hypothesis); (2) the solar declination δ (equinoctial hypothesis), and (3) the solar P angle (RM effect). Note that δ is plotted inversely.

Table 1
Observed times of spring and fall maxima in various geomagnetic indices

			Date	
Reference	Index	Time period	Spring maximum	Fall maximum
Bartels (1932)	u_1	1872–1930	5 April	4 October
Chapman and Bartels (1940)	*C*	1906–1933	22 March	20 September
Fraser-Smith (1972)	*ap*	1932–1969	25 March	25 September
Damaske (1977)	*Km*	1959–1972	17 March	18 September
Orlando et al. (1993)	*aa*	1868–1989	26 March	25 September

modulated by the angle between the solar wind flow direction and Earth's dipole axis, the key angle in the equinoctial hypothesis.

In principle, it should be possible to use the phase of geomagnetic variations predicted by the three classical hypotheses to determine which is the dominant mechanism. For the axial, equinoctial, and Russell–McPherron hypotheses peak activity for the spring (fall) equinox should occur at 7 March (9 September), 21 March (23 September), and 7 April (11 October), respectively. These dates correspond to maxima of the (absolute) solar B_0 angle (axial hypothesis) and the (absolute) solar P angle (RM mechanism) and minima of the (absolute, inverted) solar declination δ (equinoctial effect). The solar B_0 angle corresponds to Earth's heliographic latitude; the solar declination δ is the Sun's latitude in celestial coordinates; and the solar P angle is the position angle of the northern extremity of the Sun's rotation axis, measured eastward from the north point of the disk. The solar declination is equal to the daily average of the complement of the acute angle between the Earth–Sun line and Earth's dipole axis, while the P angle corresponds to the complement of the daily average of the acute angle between the z-axis of the GSM coordinate system and the solar-equatorial plane, measured in the y–z (GSM) plane. Absolute values of B_0, P, and (inverted) δ over the course of a year are plotted in Fig. 1.

The results of several previous timing studies are summarized in Table 1. It can be seen that analyses based on "modern" indices with the longest baselines, namely *ap* (Fraser-Smith, 1972) and *aa* (Orlando et al., 1993), support the equinoctial hypothesis over the axial and RM mechanisms (see also Green, 1984). This is particularly clear when aberration (Roosen, 1966; Mayaud, 1974b), the apparent angular offset (in radians) of the Sun determined by the ratio of Earth's orbital speed ($29.8\ \mathrm{km\ s^{-1}}$) to the average solar wind speed, is taken into account. For an average wind speed of $438\ \mathrm{km\ s^{-1}}$ (1963–98), the theoretical (aberration-adjusted) maxima for the equinoctial hypothesis [25 March (21 March + 4 days) and 27 September (23 September + 4 days)] both fall within the ±3–4 day uncertainties of the peak dates determined experimentally by Fraser-Smith (1972) and Orlando et al. (1993).

Nevertheless, the most recent studies on the phase of the semiannual variation have produced ambiguous conclusions. For example, Orlando et al. (1993) suggested that the spring maximum they found of March 26 ± 4 days could have resulted from a combination of the axial and RM effects producing a peak phase between those predicted for the two hypotheses. They ignored the equinoctial hypothesis that provided the best agreement with the data. In a superposed epoch analysis of the *ap* data, Clúa de Gonzalez et al. (1993) found activity peaks occurring near each of the theoretically predicted dates for the three hypotheses and were unable to come to a conclusion regarding which, if any, mechanisms might be dominant.

Given the recent evidence supporting the equinoctial hypotheses as the principal cause of the seasonal variation of geomagnetic activity (Cliver et al., 2000), we reexamined the phase data bearing on the origin of this modulation. For the long running *aa* (1868-present) data set, we determined the times of peak and minimum geomagnetic activity during the course of the year and, following Roosen (1966), we compared 30-day smoothed curves of the data and the relevant angle (B_0, δ, P) for the three mechanisms to assess the overall fidelity of the observations and predictions. We also obtained a three-parameter fit of the smoothed yearly curve of *aa*, using a composite function based on the annual variations of B_0, δ, and P. Our analysis is presented in Section 2 and the results are summarized and briefly discussed in Section 3.

2. Analysis

2.1. Dates of maxima and minima

Previous phase studies of the seasonal variation have only considered times of maxima. In principle, of course, the times of minima should serve as an equally valid test, and we will examine these as well.

For the 1868–1998 *aa* data set, we obtained daily averages for the first 365 days of each year (neglect of the extra day during leap years has a negligible effect on the results). We used a Fast Fourier Transform routine to obtain initial values for the coefficients and phases of the sine terms for the annual and semiannual variability and then made a four-parameter fit (constant plus annual and semiannual terms) to the data. From this fit, we obtained the times of seasonal maxima and minima (top of Table 2) with statistical uncertainties of ±1.9 days. In the bottom of Table 2 we list the theoretically predicted times of maxima and minima for the axial, RM, and equinoctial mechanisms. For the equinoctial hypothesis, the listed theoretical times are averages of the exact times (to 0.1 day) of equinoxes and solstices for each year over the 1868–1998 interval considered. The observed dates are in closest agreement with the predictions of the equinoctial hypothesis; the differences between predicted and observed dates, given in the "Delta" row for the four seasons, average to +5.1 days. Corresponding average differences for the axial and RM mechanisms are −∼19 days and +∼11 days, respectively. An average lag of 5.1 ± 1.9 days from the equinoctial dates encompasses a lag of 4.0 days, corresponding to the aberration effect for an average solar wind speed of 438 km s^{-1}, the average wind speed measured during the space age.

2.2. Annual profiles of geomagnetic activity

In Fig. 1, it can be seen that in addition to having different times of maxima and minima, the three hypotheses for the seasonal variation predict different overall profiles for the modulation. In particular, the equinoctial hypothesis predicts relatively sharp maxima and broad minima in relation to the axial and RM mechanisms. Roosen (1966) was the first to consider the predicted shapes of the modulation as a test of the various hypotheses. Using the *ap* data set over the period from 1932–66, he determined that the 30-day smoothed geomagnetic data bore greater resemblance to the similarly smoothed annual variation of the solar declination δ than to that for B_0. Here we extend Roosen's analysis for the *aa* index by considering all three hypotheses. The results are given in Figs. 2 and 3 which contain comparisons of the data (30-day smoothed with every fifth day plotted) and the smoothed theoretical curves. In both figures, the δ curve has been shifted four days to the right to make allowance for aberration. It can be seen that the *aa* data have greater fidelity to the equinoctial hypothesis ($|r| = 0.96$) than to the axial hypothesis ($r = 0.76$) and RM effect ($r = 0.86$), respectively.

2.3. Curve fits to the data based on yearly variations of B_0, δ, and P

To quantify the relative contributions of the three mechanisms to the seasonal variation of geomagnetic activity, we fitted the smoothed (30-day running averages, plotted at 5-day intervals) annual variation of the *aa* index to a three-parameter function consisting of the similarly smoothed annual variations of B_0, δ (aberration shifted), and P,

$$aa = A_1 B_0 + A_2 \delta + A_3 P. \qquad (1)$$

The best fit (Fig. 4) corresponded to coefficients of $A_1 = 0.16 \pm 0.03$, $A_2 = 0.58 \pm 0.07$, and $A_3 = 0.20 \pm 0.04$.

2.4. Analysis considerations: aberration and smoothing interval

In Section 2.1 we showed that, on average, the experimentally determined minima and maxima of the peaks in

Table 2
Observed times of spring and fall maxima and summer and winter minima in the 1868–1998 *aa* data set, compared with predictions of axial, Russell (RM), and equinoctial hypotheses

	Spring maximum	Fall maximum	Summer minimum	Winter minimum
Observed date	27.1 March	27.3 September	26.6 June	27.8 December
Theoretically predicted dates				
Axial	7 March	9 September	7 June	8 December
RM	7 April	11 October	7 July	6 January
Equinoctial[a]	21.1 March	23.4 September	21.8 June	22.3 December
Delta (days) (Equinoctial)	+6.0	+3.9	+4.8	+5.5

[a] Not adjusted for aberration.

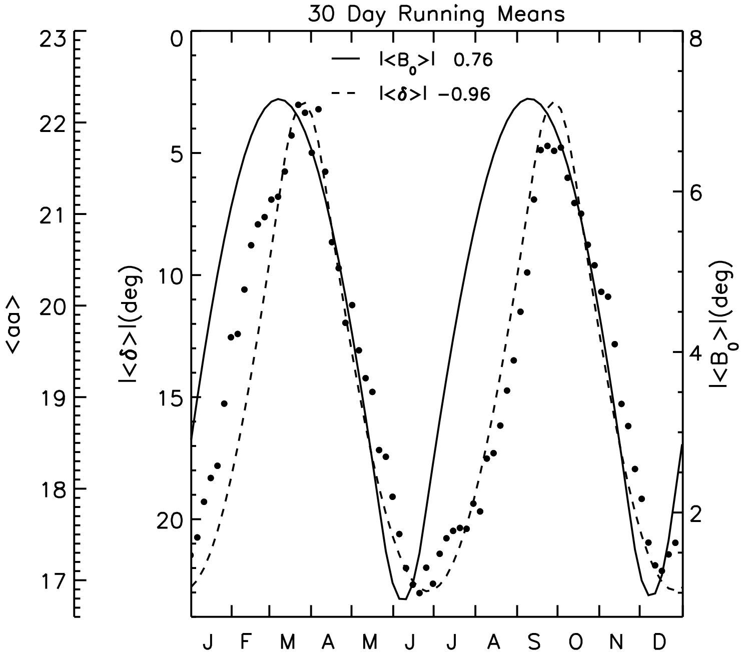

Fig. 2. Plot of 30-day running averages of the geomagnetic *aa* index (1868–1998) vs. day of the year, plotted at 5-day intervals. Also plotted are the smoothed (absolute) solar B_0 angle, the controlling angle in the axial hypothesis, and the smoothed (absolute, inverted) solar declination δ, specifying the annual variation of geomagnetic activity under the equinoctial hypothesis. The correlation coefficients between the angles and data are given.

the *aa* curve lagged extrema in the annual variation of the solar declination angle by 5.1 ± 1.9 days. Given the relatively small statistical uncertainty in the observed phases and the other evidence (e.g., Cliver et al., 2000) for a dominant equinoctial effect, we assumed that the 5.1 day lag was primarily due to aberration and factored a 4.0 day lag, corresponding to current solar wind speeds, into our correlation analysis in 2.2 and the curve fitting analysis in Section 2.3. The measured lag of 5.1 days may reflect variability in the average solar wind speed over the last ~ 130 years and may also include (non-balancing) contributions from the axial and RM effects. Thus, it is important to note that not making this assumption (i.e., 4.0 day adjustment for δ) does not significantly change our results. If we do not include the lag in the correlation analysis in Figs. 2 and 3, the correlation coefficient between the smoothed *aa* and δ curves changes from $|r| = 0.96$ to 0.95. Omitting the lag from δ in the curve fitting analysis in Fig. 4 changes the three coefficients to: $A_1\,(\text{axial}) = 0.11 \pm 0.04$, $A_2\,(\text{equinoctial}) = 0.55 \pm 0.07$, and $A_3(\text{RM}) = 0.26 \pm 0.03$.

Roosen (1966) selected the 30-day smoothing interval as a result of visual inspection. Shorter intervals would produce somewhat lower correlation coefficients in Figs. 2 and 3, but the relative differences between the three fits does

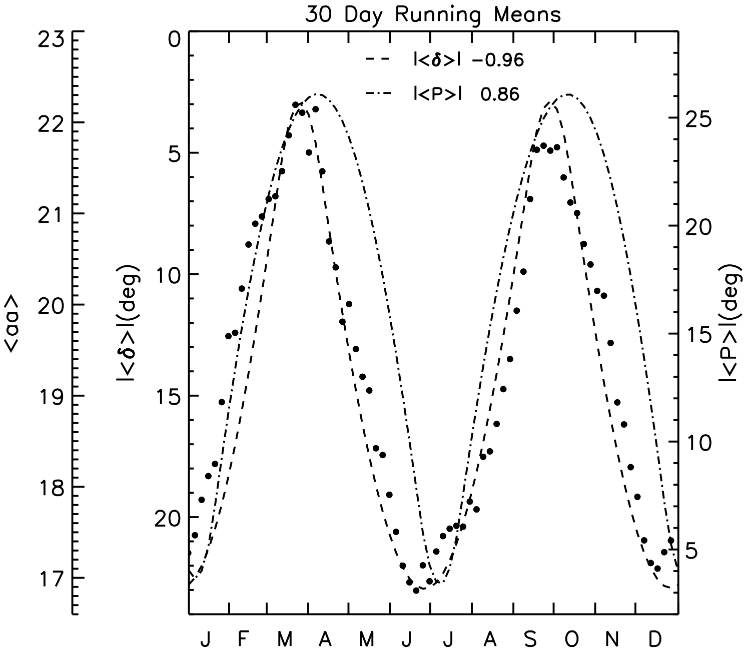

Fig. 3. Plot of 30-day running averages of the geomagnetic *aa* index (1868–1998) vs. day of the year, plotted at 5-day intervals. Also plotted are the smoothed (absolute) solar P angle for the RM effect and the smoothed solar declination δ (absolute, plotted inversely), specifying the annual variation of geomagnetic activity under the equinoctial hypothesis. The correlation coefficients between the angles and data are given.

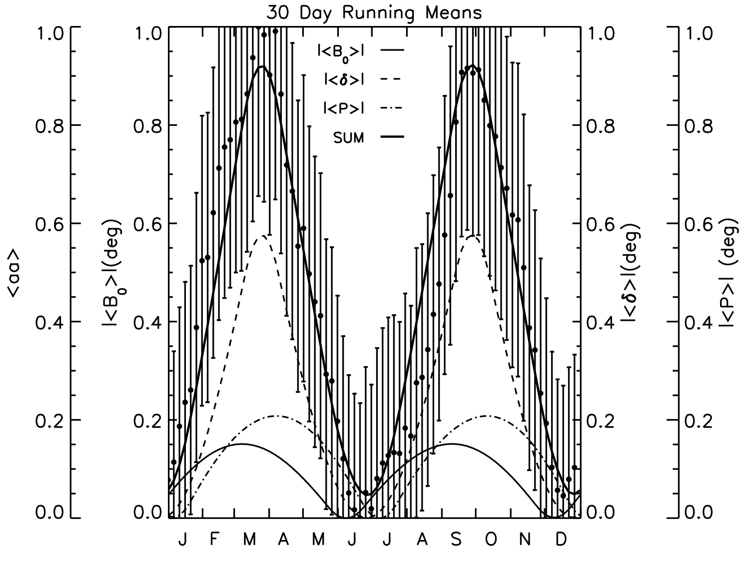

Fig. 4. Plot of 30-day running averages of *aa* data (1868–1998), normalized to 1.0, with every fifth point plotted and statistical error bars shown, vs. day of the year. The bold line is the best-fit line to the data of a function consisting of the sum of smoothed curves for the “governing angles” of the principal modulation hypotheses: axial (B_0), equinoctial (δ), and RM (P).

not change significantly. For example, for unsmoothed data (daily averages of *aa*), the correlation coefficients for B_0, P, and δ are 0.56, 0.65, and −0.73, respectively, while for a smoothing interval of 60 days, the corresponding numbers are 0.77, 0.89, and 0.97. For the curve-fitting analysis in Fig. 3, the coefficient of the equinoctial term increases relative to the other two components as the smoothing interval is increased. For an interval of 10 days, all three components have coefficients ∼0.25; for intervals $\geqslant 25$ days, the coefficients become relatively constant near the values determined in Section 2.3.

3. Summary and discussion

Each of the three classic hypotheses for the seasonal variation of geomagnetic activity predicts spring and fall maxima. As we have shown here, however, the precise timing of the maxima (and minima) determined for the extended (∼130 year) *aa* data clearly favors the equinoctial hypothesis (Table 2), particularly when aberration is taken into account. In addition, following an analysis originally performed by Roosen (1966), we have shown that the overall shape of the seasonal modulation, with relatively narrow maxima and broad minima, agrees better with the annual variation of the solar declination (which governs, on average, the equinoctial hypothesis) than with the solar B_0 angle (axial hypothesis) or P angle (RM effect) (Figs. 2 and 3). Finally, fitting the annual variations of *aa* with a composite function of B_0, δ, and P indicates that the equinoctial effect is the principal contributor to its seasonal variation.

Generally similar results (not shown here) for each of these analyses (timing, shape, relative contributions) were obtained for shorter intervals of data for the *ap* (since 1932) and *am* (since 1959) indices. Such agreement is not unexpected because the mid-latitude range indices are highly correlated (Mayaud, 1980).

The three lines of phase/profile evidence presented here for a dominant equinoctial effect in the seasonal variation of average values of the mid-latitude range indices are consistent with: (1) the imprint of the equinoctial hypothesis on the universal time variation of *am*, shown most recently by Cliver et al. (2000) and previously by Svalgaard (1977) and others, and (2) independent quantitative assessments of the relative contributions of the modulation mechanisms to the seasonal variation of *am* (e.g., Berthelier, 1976; Cliver et al., 2000).

Acknowledgements

We thank both referees for helpful comments. This work was supported by AFRL Contract No. F19628-98-C-0054.

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