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Origins of the semiannual variation of geomagnetic activity in 1954 and 1996

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Abstract. We investigate the cause of the unusually strong semiannual variation of geomagnetic activity observed in the solar minimum years of 1954 and 1996. For 1996 we separate the contributions of the three classical modulation mechanisms (axial, equinoctial, and Russell-McPherron) to the six-month wave in the aa_m index and find that all three contribute about equally. This is in contrast to the longer run of geomagnetic activity (1868–1998) over which the equinoctial effect accounts for ~70% of the semiannual variation. For both 1954 and 1996, we show that the Russell-McPherron effect was enhanced by the Rosenberg-Coleman effect (an axial polarity effect) which increased the amount of the negative (toward Sun) [positive (away from Sun)] polarity field observed during the first [second] half of the year; such fields yield a southward component in GSM coordinates. Because this favourable condition occurs only for alternate solar cycles, the marked semiannual variation in 1954 and 1996 is a manifestation of the 22-year cycle of geomagnetic activity. The 11-year evolution of the heliospheric current sheet (HCS) also contributes to the strong six-month wave during these years. At solar minimum, the streamer belt at the base of the HCS is located near the solar equator, permitting easier access to high speed streams from polar coronal holes when the Earth is at its highest heliographic latitudes in March and September. Such an axial variation in solar wind speed was observed for 1996 and is inferred for 1954.

Key words. Magnetosphere (solar wind – magnetosphere interactions; storms and substorms)

1 Introduction

The cause of the semiannual variation of geomagnetic activity, characterized by stronger and more frequent storms in spring/fall vs. summer/winter, is a long-standing question (e.g. Sabine, 1856) for which three mechanisms have been proposed. The equinoctial hypothesis (Bartels, 1925, 1932; McIntosh, 1959; Svalgaard, 1977) is governed by the ψ angle between the solar wind flow direction and the Earth's dipole axis. Under this hypothesis, activity maximizes (for as yet unknown reasons) at the equinoxes when ψ is 90°. The key angle in the axial hypothesis (Cortie, 1912) is the heliographic latitude of the Earth (B_O). In early March and September the Earth is at its maximum angular distance (~7°) from the solar equatorial plane and thus more closely aligned with both the sunspot zones and coronal holes that extend down from the solar poles. In the Russell-McPherron mechanism (Russell and McPherron, 1973), magnetic fields in the solar equatorial plane have a peak southward component at the Earth in Geocentric Solar Magnetospheric (GSM) coordinates in early April or October, depending on their polarity.

While all of these mechanisms contribute to the semiannual variation, their relative contributions have long been a matter of debate (e.g. Mayaud, 1974a; Russell and McPherron, 1974). Recently, various authors (Cliver et al., 2000, 2001, 2002; Lyatsky et al., 2001; Temerin and Li, 2002; O'Brien and McPherron, 2002) have argued that the equinoctial hypothesis plays a more important role vis-à-vis the competing axial and (in particular) Russell-McPherron (RM) mechanisms than has previously been thought to be the case. Cliver et al. (2000) and Svalgaard et al. (2002) calculated that, on average, the equinoctial hypothesis accounts for 65–75% of the amplitude of the six-month wave in the geomagnetic am index.

The present study does not deal with average conditions. Occasionally, the semiannual variation of geomagnetic activity is so pronounced that one can readily identify the equinoctial peaks and solstitial valleys in plots of daily averages of geomagnetic indices during the year. The solar minimum years of 1954 and 1996 were two such intervals. In this study we ask why the six-month wave was so prominent during these years. Our analysis is presented in Sect. 2 and the results are discussed in Sect. 3.

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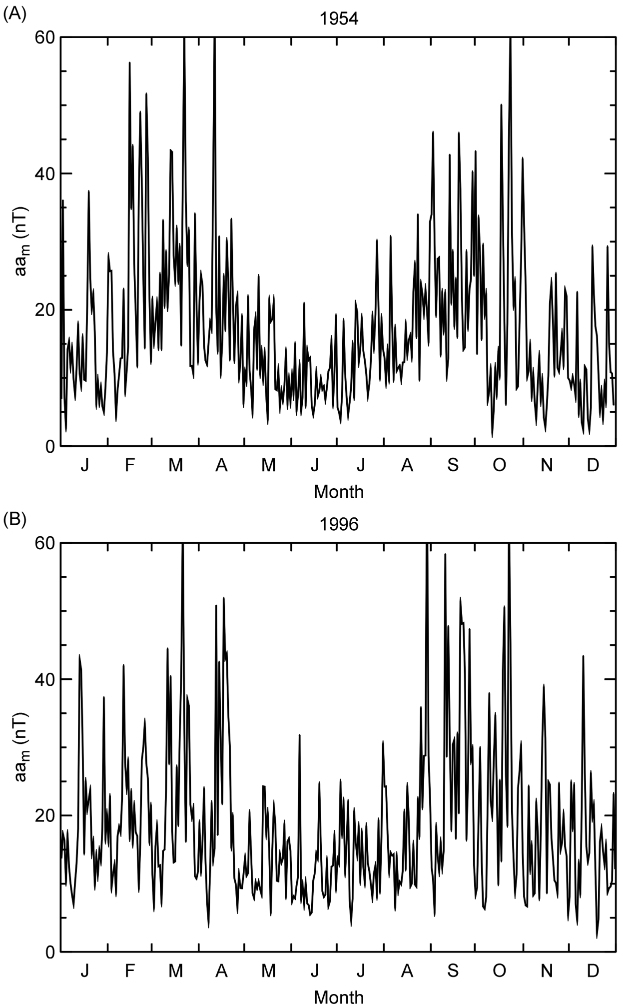

Fig. 1. Plots of daily values of the aa_m index for **(a)** 1954 and **(b)** 1996.

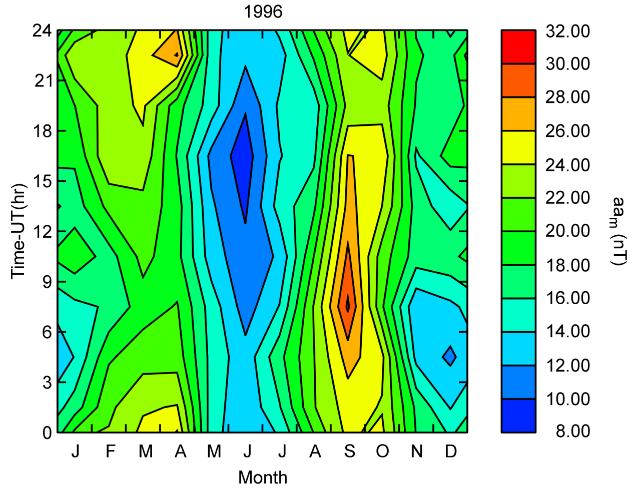

Fig. 2. Diurnal/seasonal variation of the aa_m index during 1996.

2 Analysis

2.1 Selection of years

To identify years with a pronounced semiannual variation, we used the aa_m index recently introduced by Svalgaard et al. (2002). The aa_m index is the aa index[1] (Mayaud, 1972, 1980), available from 1868–1998, modified to have the correct universal time variation. We correlated the diurnal/seasonal matrix (8×12; 3 h, 1 month) of aa_m values for each of the 131 years with the equinoctial angle (ψ), the Russell-McPherron angle (the angle between the z-axis in the GSM coordinate system and the solar equatorial plane, measured in the $y - z$ (GSM) plane), and the axial angle (B_O). Because of the $\sim$11° offset of the Earth's dipole axis to the rotation axis, both the equinoctial and Russell-McPherron mechanisms produce a Universal Time variation (UT), as well as seasonal variation, while the axial effect has no UT dependence. From 1868–1998, 37 indiviudal years had aa_m-ψ angle correlation coefficients ≥ 0.5, in comparison with 9 such years for B_O and only 4 years (≤ -0.5) for the RM angle. We selected for further analysis the only two years that had numeric correlation coefficients $\geq$ 0.5 in all three indices: 1954 ($r = 0.66(\psi)$; $r = -0.50$(RM); $r = 0.59(B_O)$) and 1996 ($r = 0.70(\psi)$; $r = -0.51$(RM); $r = 0.56(B_O)$). Our technique thus identified years that had strong semiannual variations that could be plausibly accounted for in terms of any one, or a combination, of the three classic modulation hypotheses. Figure 1a and b give plots of daily values of aa_m for 1954 and 1996, respectively. In both cases, the six-month wave in geomagnetic activity is readily discernible.

[1]The aa index is a mid-latitude range index based on maximum excursions of the horizontal (H) or declination (D) components of the field over a 3-h interval after removing the regular variation (S_R). aa is based on two nearly-antipodal stations in England and Australia; because the stations are not exactly antipodal, the UT-dependence is distorted, hence, the correction as described.

2.2 Origins of the semiannual variation of geomagnetic activity in 1996

2.2.1 ψ-angle normalization

A diurnal/seasonal plot of the aa_m index for 1996 is given in Fig. 2. To remove the contribution from the equinoctial mechanism, we follow the procedure of Svalgaard et al. (2002) (see also O'Brien and McPherron, 2002) and multiply aa_m by 0.864 $(1 + \cos^2 \psi)^{2/3}$ to obtain the ψ-normalized aa_{m0} index. Figure 3 gives plots of monthly averages of (a) southward magnetic field (B_S, in GSM coordinates), (b) solar wind speed (v), (c) the aa_m index, and (d) the aa_{m0} index for 1996. An FFT analysis of the aa_m and aa_{m0} indices shows that the ψ-normalization removes only $\sim$35% of the amplitude of the second harmonic (given in the figure) vs. the 65–75% figure obtained by Cliver et al. (2000) and Svalgaard et al. (2002) for the contribution from the equinoctial effect.

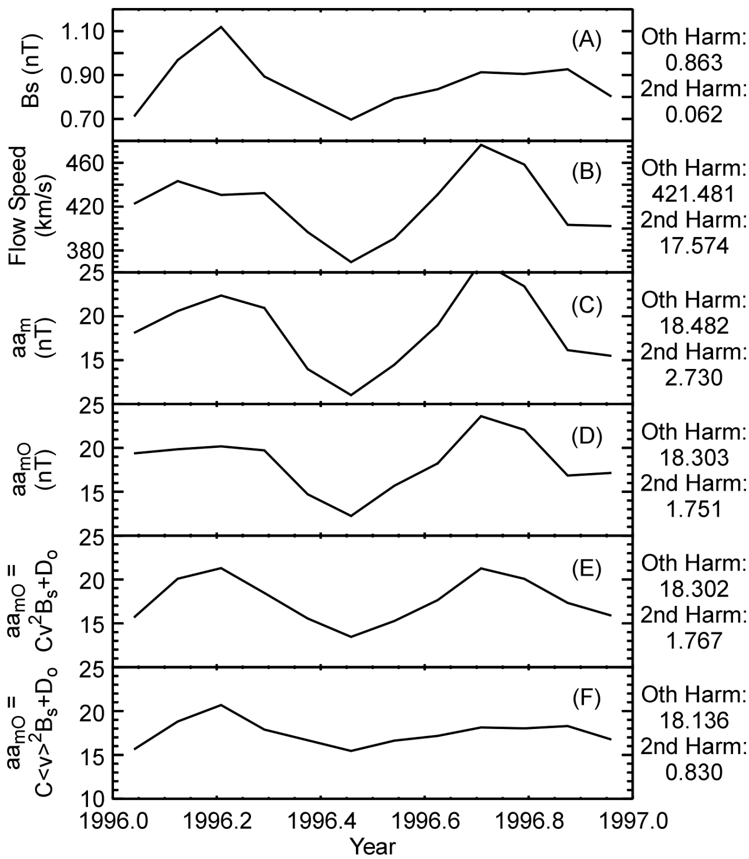

Fig. 3. Monthly averages for 1996 of **(a)** southward magnetic field (B_s), **(b)** solar wind flow speed (v), **(c)** aa_m index, **(d)** "observed" aa_{m0} index, **(e)** calculated aa_{m0} index (from Eq. 1; $C = 7.551 \times 10^{-5}$, $D_O = 6.554$), and **(f)** calculated aa_{m0} index with solar wind flow speed (v) held constant at its yearly average of 421km s^{-1}. The average value (0th harmonic) and coefficient of the 2nd harmonic of each parameter are given in the right-hand margin.

2.2.2 Contributions from the Russell-McPherron and axial mechanisms

The semiannual variations of B_S (Fig. 3a) and v (Fig. 3b) indicate that both the Russell-McPherron effect and the axial effect contribute to the six-month wave in aa_{m0}. To separate and quantify these contributions, we obtained the following relationship between monthly averages of aa_{m0} and solar wind parameters for 1996, assuming the standard functional form between these variables deduced by various authors (e.g. Feynman and Crooker, 1978)

$$aa_{m0} = 7.551 \times 10^{-5} v^2 B_S + 6.554\,. \qquad (1)$$

Figure 3e shows that aa_{m0} (calculated from Eq. 1) has an average value and second harmonic coefficient that are comparable to those for the observed aa_{m0} (Fig. 3d). To obtain Fig. 3f, the value of v was held constant at the 1996 annual average of 421km s^{-1}, thereby removing the axial solar wind speed contribution to the semiannual variation. The remaining ~50% (0.83/1.77) of the semiannual variation of aa_{m0} is attributed to the Russell-McPherron effect. (An essentially identical result is obtained by holding B_S constant.) Approximately equal contributions for the axial and Russell-McPherron effects are consistent with correlations of the diurnal/seasonal matrix of aa_{m0} with $B_O (r = 0.50)$ and the RM angle ($r = -0.47$). Thus, we conclude that for 1996, all three of the classic modulation mechanisms contributed about equally to the six-month wave in the aa_m index.

2.2.3 Causes of the enhanced Russell-McPherron and axial contributions

The Russell-McPherron mechanism assumes that the interplanetary magnetic field measured at the Earth is equally likely to be pointed inward or outward during the year. For long intervals this is a good assumption, e.g. for the 1963–2000, we find that B_X is positive (negative) 50.4% (49.6%) of the time. For shorter intervals of time, however, the polarity mix can deviate from parity. In particular, for periods near solar minimum when the heliospheric current sheet (HCS) lies close to the solar equator, the Earth can find itself preferentially in one polarity or the other for six month intervals as it ranges between ~7° N and ~7° S in heliospheric latitude. Rosenberg and Coleman (1969) were the first to draw attention to this axial polarity effect. The Rosenberg-Coleman polarity effect is evident in 1996. During this year, the solar wind polarity was biased negative (inward) during the first half of the year and positive (outward) during the second half (Fig. 4), circumstances under which the Russell-McPherron coordinate transformation from Geocentric Solar Equatorial (GSEq) to GSM coordinates yields a southward pointing magnetic field component. In all, the magnetic polarity at the Earth was favourable for 63% of all hours during

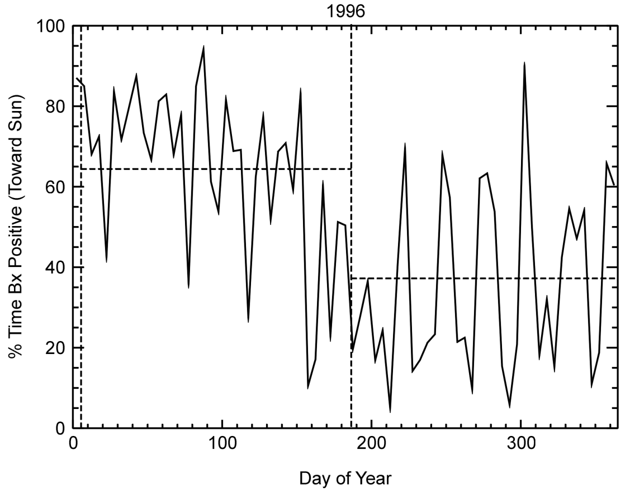

Fig. 4. Solar wind magnetic polarity distribution (5-day averages) at the Earth during 1996. Fields with positive (negative) B_x are directed toward (away from) the Sun. The dashed vertical lines indicate mimima (favourable polarity cross-over times) for the Russell-McPherron effect. The dashed horizontal lines give average percentages of the time B_x is positive for intervals bounded by these crossings (the second interval is truncated on 31 December). Note that B_x has the opposite sign of the solar/solar wind magnetic polarity.

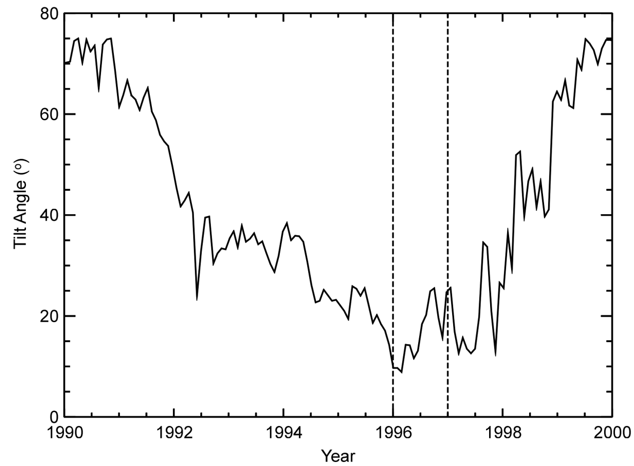

Fig. 5. Evolution of the "tilt angle" of the heliospheric current sheet from 1990–2000. The dashed vertical lines bracket 1996.

1996, vs. the ∼50% long-term average, indicating a Russell-McPherron effect that was theoretically ∼25% stronger than usual. Comparison of the coefficients of the second harmonics in FFT analyses of B_s for 1996 (0.62) and the interval 1963–2000 (0.38) indicates an actual increase of ∼60%.

Figure 5 shows the evolution of the "tilt angle" (Smith and Thomas, 1986) of the HCS during the period from 1990–2000. The tilt angle is obtained from computed coronal magnetic field maps of the Wilcox Solar Observatory at Stanford University (Hoeksema, 1989) by averaging the maximum latitudinal excursions (north and south) of the coronal neutral line during each Carrington rotation. The low tilt angles during 1996 indicate that the Sun's "magnetic equator" is more-or-less aligned with its heliographic equator. During these solar minimum conditions, high-speed streams from polar coronal holes reach relatively low latitudes (as revealed by Ulysses, Bame et al., 1993; Phillips et al., 1995; see also Hundhausen, 1977) and are more likely to intercept the Earth at its maximum excursions north and south of the solar equator. Bohlin (1977) was the first to point out that this axial effect on high-speed streams from coronal holes could contribute to the semiannual variation of geomagnetic activity (Fig. 6 from Bohlin, 1977).

2.2.4 Contribution from the evolution of coronal holes during 1996

In the analysis in Sect. 2.2.2, we assumed that the source of the solar wind is constant during the year and that all wind speed variation (Fig. 3b) is due to the Earth's annual excursion in heliographic latitude. Examination of coronal hole maps based on He 10 830 observations from Kitt Peak (National Solar Observatory website) and derived coronal hole maps provided by C. N. Arge (private communication, 2002) based on a potential field source surface model and a current sheet model (Arge et al., 2002) generally validates this assumption. High-speed streams during the first half of the year appear to originate exclusively in the south polar coronal hole, while the most prominent period of high-speed flow during the second half of the year (11–23 September) is attributed to the north polar coronal hole. Non-polar coronal holes do play a more important role in the second half of the year, however. For example, the "Elephant's Trunk" polar coronal hole extension (identified during the Whole Sun Month (8 August – 10 September) campaign; Galvin and Cole, 1999; Zhao et al., 1999) and its remnants contributed to geomagnetic activity around the fall equinox.

2.3 Origins of the semiannual variation of geomagnetic activity in 1954

A diurnal/seasonal plot of the aa_m index for 1954 is given in Fig. 7. For this year, the coefficient of the second harmonic for the aa_m index is larger than was the case for 1996 (3.81 vs. 2.73; see Fig. 1). Normalizing the 1954 aa_m data for the ψ angle to obtain aa_{m0} removes ∼25% of the amplitude of the six-month wave (0.92/3.81). Because solar wind data are unavailable for 1954, we were unable to apportion the six-month wave in aa_{m0} between the Russell-McPherron and axial wind speed effects. There is no compelling evidence to suggest that one or the other is dominant, however. Correlating the 8×12 diurnal/seasonal variation plot of aa_{m0} for 1954 with the Russell-McPherron and B_O angles yields $r = -0.49$ and $r = 0.59$, respectively (statistically identical).

Using Eq. (1), we reproduced the amplitude of the six-month wave in aa_{m0} values observed for 1954 by artificially

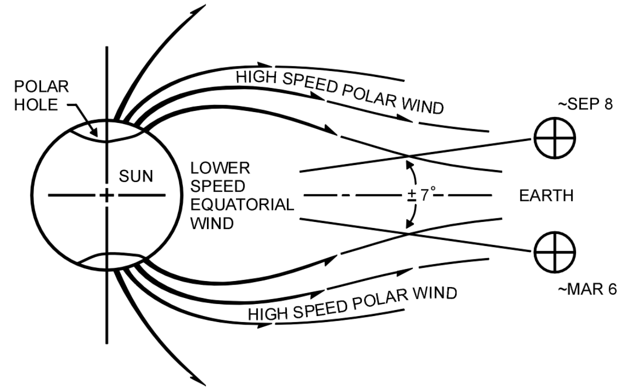

Fig. 6. Schematic showing how high-speed streams from polar coronal holes can contribute to the semiannual variation of geomagnetic activity via an axial effect (after Bohlin, 1977).

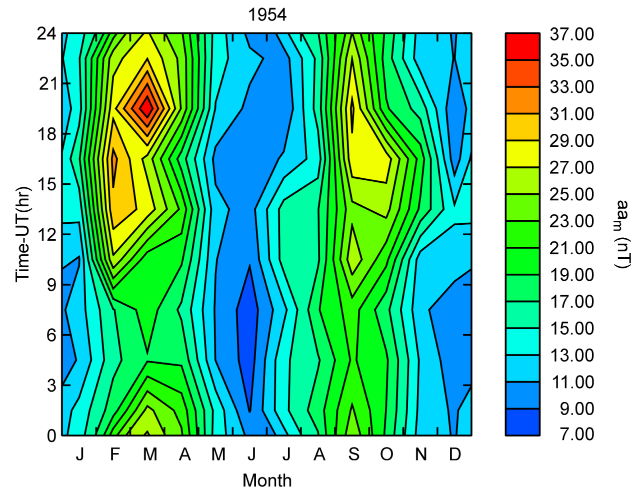

Fig. 7. Diurnal/seasonal variation of the aa_m index during 1954.

increasing the amplitude of the six-month wave in either v or B_s data from 1996 (by increasing monthly averages of these parameters by a fixed percentage (5% for v, 10% for B_s) during the six equinoctial months and decreasing them by the same percentage during solstitial months) and using monthly observed values from 1996 for the other parameter. Since the enhanced amplitudes of the semiannual variations in v or B_s that were required to model the semiannual variation in aa_{m0} were within the ranges of variability of these parameters for recent solar cycle decline/minimum epochs, there is no reason to suspect that the mechanisms giving rise to the strong six-month wave in aa_{m0} in 1954 were qualitatively different from those (i.e. the axial wind speed and Russell-McPherron effects) acting in 1996.

Svalgaard (1972) introduced a polarity index of the interplanetary magnetic field based on diurnal patterns observed in ground-based polar magnetograms. Basically, a day is classified as having toward (away) polarity if the vertical component of the magnetic field at a near pole station has a broad, positive (negative) perturbation between magnetic noon and local noon. A third "mixed" classification is used for days that do not fit neatly into either the toward or away groups. If we count mixed polarity days as half favourable and half unfavourable, we find that, similarly to 1996, 62% of all days during 1954 had a favourable Russell-McPherron polarity (Fig. 8). Power spectral analysis of the aa_m data in Fig. 1a yields a strong peak at 27 days, indicating persistent recurrent storms (see Tandon, 1956), and solar eclipse observations at mid-1954 (Fig. 9, taken from Vsekhsvjatsky, 1963; see also Schatten et al., 1978) reveal a streamer belt (base of the HCS) aligned with the solar equator.

2.4 The semiannual variation of geomagnetic activity in 1954 and 1996 and the 22-year variation of geomagnetic activity

The "halfwave rectifier" nature of the magnetosphere (Arnoldy, 1971; Burton et al., 1975) implies that geomagnetic activity will be enhanced via the Russell-McPherron effect when the Rosenberg-Coleman polarity effect produces enhanced positive polarity in spring and negative polarity in fall. Due to solar polarity reversal every 11 years at solar maximum, such conditions occur at alternate solar minima, contributing to an observed 22-year variation in geomagnetic activity (Chernosky, 1966; Cliver et al., 1996). This explanation for the 22-year geomagnetic cycle was first pointed out by Russell and McPherron (1973). The years 1954 and 1996 are separated by $\sim 2 \times 22$ years and are thus a manifestation of this periodicity.

3 Summary and discussion

We have examined the cause of the semiannual variation of geomagnetic activity for two solar minimum years in which the six-month wave is apparent in daily averages of the aa_m index. During these years, both the Russell-McPherron and axial mechanisms make much larger contributions (each accounting for ~33% of the total) to the semiannual variation than usual. For comparison, Cliver et al. (2000) and Svalgaard et al. (2002) found that, in general, these two mechanisms combined contribute only ~30% to the six-month wave, with the remainder due to the equinoctial effect.

3.1 What was different about 1954 and 1996?

Years such as 1954 and 1996 with strong, well-defined semiannual variations are rare, with only these two years out of 131 meeting our selection criteria (Sect. 2.1). What was unusual about these years? As seen in Figs. 4 and 8 the solar wind polarity, rather than being more or less evenly mixed throughout the year, as it is in long-term averages, was preferentially inward in spring and outward in fall, circumstances that favour the creation of a southward field in the GSM coordinate system under the Russell-McPherron effect. The preference for one solar magnetic field polarity during the first half of the year and the other during the second half is

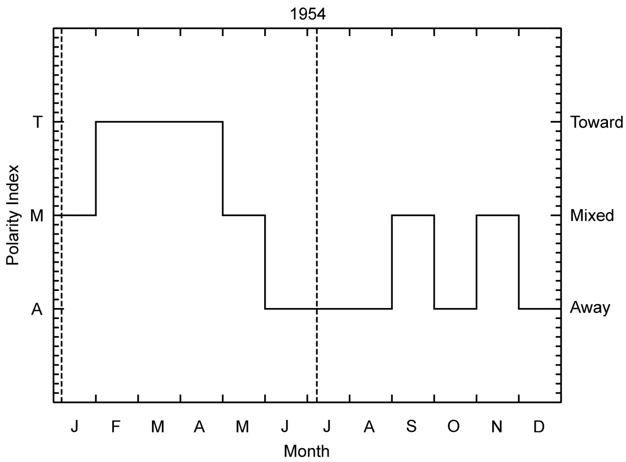

Fig. 8. Monthly solar wind magnetic polarity indices (Svalgaard, 1972) for 1954. A polarity was judged to be dominant during a month if it occurred for > 50% of the days. The dashed vertical lines indicate minima for the Russell-McPherron effect. Toward and away is with reference to the Sun.

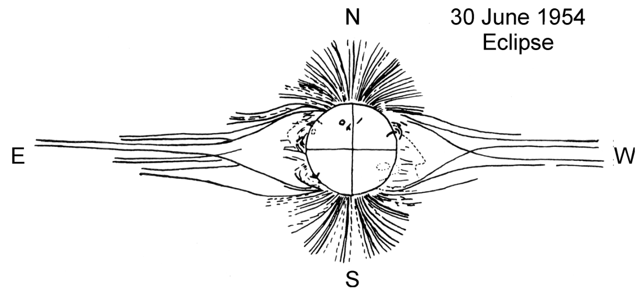

Fig. 9. Observation of the solar eclipse of 30 June 1954 (Vsekhsvjatsky, 1963) showing the alignment of streamers with the solar equator.

an axial polarity effect discovered by Rosenberg and Coleman (1969). It occurs during solar minimum years such as 1954 and 1996, when the heliographic equator and streamer belt are closely aligned (Figs. 5 and 9). At these times, the Earth will tend to sample one solar wind polarity when its heliographic latitude is positive and the opposite polarity for negative latitudes. Because the Sun reverses polarity every 11 years, the favourable polarities for the Russell-McPherron effect (inward in spring and outward in fall) occur at alternate solar minima. Thus, the combination of the Rosenberg-Coleman and Russell-McPherron effects contribute to the observed 22-year cycle of geomagnetic activity (Chernosky, 1966; Russell and McPherron, 1973; Cliver et al., 1996), and the strong semiannual variation in 1954 and 1996, separated by $\sim 2\times 22$ years, is a reflection of the 22-year solar magnetic cycle.

The semiannual variation of geomagnetic activity in 1996 also benefited from a stronger than usual solar wind speed variation. The value of $\sim$18km s^{-1} we find for the coefficient of the second harmonic of the solar wind speed for 1996 (Fig. 3b) compares with $\sim$3km s^{-1} for the 1963–1997 interval. A comparably enhanced (to 1996) six-month wave in solar wind speed is inferred for 1954. We attribute the semiannual variation in solar wind speed during 1954 and 1996 primarily to an axial effect involving the Sun's polar coronal holes (Bohlin, 1977). The quasi-alignment of the heliomagnetic and heliographic equators at solar minimum enables the Earth to access high-speed streams from alternate polar coronal holes on its excursions to $\sim 7^\circ$ N (S) heliolatitude in September (March) (Fig. 6).

Four other solar minimum years (McKinnon, 1987) with favourable Rosenberg-Coleman polarity occurred during the 1868–1998 interval for which we have aa_m data: 1889, 1913, 1933, and 1976. None of these years satisfied our selection criteria based on correlations of the aa_m data with the key angles in the axial, Russell-McPherron and axial hypotheses. Correlation coefficients obtained were as follows:
1889 ($r = 0.44(\psi)$; $r = -0.25$(RM); $r = -0.02(B_O)$);
1913 ($r = 0.48(\psi)$; $r = -0.43$(RM); $r = 0.23(B_O)$);
1933 ($r = 0.52(\psi)$; $r = -0.52$(RM); $r = 0.16(B_O)$);
1976 ($r = 0.59(\psi)$; $r = -0.35$(RM); $r = 0.37(B_O)$).

We note that the correlation coefficients for the Russell-McPherron mechanism for these four years are high in comparison with all individual years from 1868–1998, ranking 63rd, 9th, 2nd, and 23rd, respectively. Differences in the degree of correlation with the three angles between the six favourable polarity minima are attributed to the vagaries of solar activity that can disrupt (or enhance) the seasonal-UT patterns of the geometry-based drivers of the semiannual variation.

3.2 The Rosenberg-Coleman effect

When considering the axial effect, one generally thinks of sunspot fields/magnetic field strength (Cortie, 1912) or coronal holes/solar wind speed (Bohlin, 1977) but not the Rosenberg-Coleman polarity effect. As first noted by Russell and McPherron (1973), however, this semiannual variation can play an important role at alternate solar minima.

A comparison of the six favourable (1889, 1913, 1933, 1954, 1976, and 1996) and six unfavourable (1878, 1901, 1923, 1944, 1964, and 1986) minimum years in the aa_m data set highlights the interplay of the Rosenberg-Coleman effect and the Russell-McPherron mechanism. For the average of the favourable years, correlation coefficients for the three hypotheses are as follows: $r = 0.76(\psi)$; $r = -0.56$(RM); $r = 0.48(B_O)$. Corresponding coefficients for the unfavourable years are: $r = 0.60(\psi)$; $r = -0.16$(RM); $r = 0.44(B_O)$. The clear difference in the correlations with the RM angle contrasts with the relatively small differences for ψ and B_O, for which the responsible mechanisms are unaffected by the Sun's polarity reversal.

3.3 Excitation/modulation and external vs. internal sources of the semiannual variation

Mayaud (1974a) distinguished between excitation and modulation mechanisms for the semiannual variation. Excitation mechanisms include the axial and Russell-McPherron effects which increase solar wind speed and southward field strength, respectively, at the equinoxes. In comparison, the equinoctial mechanism is thought to modulate the response of the magnetosphere to the solar wind input by reducing energy transfer at the solstices (Crooker and Siscoe, 1986). Cliver et al. (2000) used a "mountain building" vs. "valley digging" metaphor to illustrate the difference between excitation and modulation mechanisms.

Recently, Lyatsky et al. (2001) have suggested that neither the amount of energy incident on the magnetosphere as in the axial and Russell-McPherron effects, nor the amount transferred to the magnetosphere via the equinoctial effect, is primarily responsible for the semiannual variation. Rather, they argued that the internal response of the system, based on the conductivity of the ionosphere in the polar regions, is the key factor. Because the variation of ionospheric conductivity at any point on the Earth is governed by the solar zenith angle, the equinoctial hypothesis is the only one of the three classic hypotheses that could produce a conductivity pattern compatible with the pattern of geomagnetic activity apparent in Fig. 2. Lyatsky et al. (2001) showed that a diurnal/seasonal plot of the solar zenith angle for the midnight auroral oval of the more sunlit hemisphere had similar contours to that of the ψ angle and the *am* index.

One argument in favour of the coupling efficiency equinoctial hypothesis (vs. an equinoctial-based conductivity variation) is the fact that the peak and minimum phases of average geomagnetic activity are shifted ∼5 days later than their theoretically predicted values (e.g.peak average *aa* occurs on 27 March and 27 September (±2 day uncertainty) rather than on 21 March and 23 September) (Cliver et al., 2002). This delay has been interpreted by Mayaud (1974b) as an aberration effect due to the Earth's orbital motion. If the seasonal variation was driven primarily by a conductivity effect, one would expect the peak phase to occur at the "unaberrated" equinox.

3.4 Maximum size of the equinoctial effect

For both 1954 and 1996, the ψ-angle normalization removed ∼1 nT from the coefficient of the second harmonic in an FFT analysis of monthly values of aa_m. In fact, applying this normalization to a perfectly flat diurnal/seasonal pattern for this index (with an amplitude of 19.3 nT corresponding to the average value of aa_m from 1868–1998) results in a coefficient of ∼1 nT (vs. 1.26 nT for the actual aa_m matrix for this interval). Thus, any value for the second harmonic coefficient of aa_m greater than ∼1 nT (for an annual average ∼19 nT), as observed for 1954 (3.8 nT; annual average = 17.2 nT) and 1996 (2.7 nT; annual average = 18.5 nT), indicates contributions from other factors, such as the axial and Russell-McPherron mechanisms or randomness in solar activity. Over the long run of data, from 1868-present, these other factors are only of secondary importance, as evidenced by the close fit of the diurnal/seasonal pattern of geomagnetic activity to that predicted by the equinoctial hypothesis (McIntosh, 1959; Svalgaard, 1977; Cliver et al., 2000) and various calculations (e.g. Berthelier, 1976; Cliver et al., 2000; Svalgaard et al., 2002), indicating the dominance of the equinoctial effect.

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