

Geomagnetic Semiannual Variation Is Not Overestimated and Is Not an Artifact of Systematic Solar Hemispheric Asymmetry

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[1] *Mursula et al.* [2011] (MTL11) suggest that there is a 22-year variation in solar wind activity that coupled with the variation in heliographic latitude of the Earth during the year, gives rise to an apparent semiannual variation of geomagnetic activity in averages obtained over several solar cycles. They suggest that the observed semiannual variation is seriously overestimated and is largely an artifact of this inferred 22-year variation. We show: (1) that there is no systematically alternating annual variation of geomagnetic activity or of the solar driver, changing with the polarity of the solar polar fields, (2) that the universal time variation of geomagnetic activity at all times has the characteristic imprint of the equinoctial hypothesis rather than that of the axial hypothesis required by the suggestion of MTL11, and (3) that the semiannual variation is not an artifact, is not overestimated, and does not need revision.

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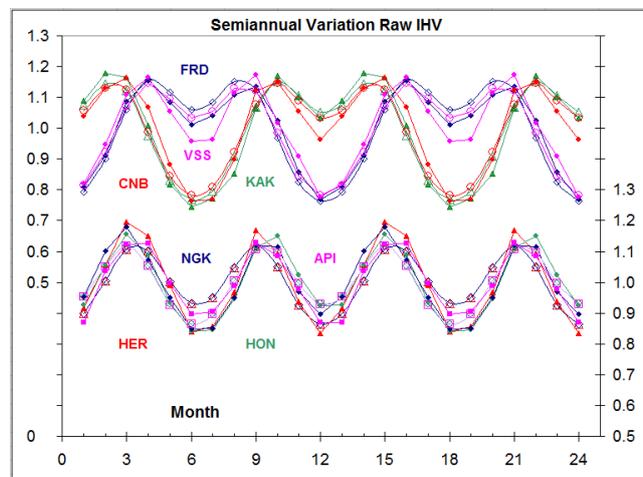


Figure 1. Semiannual variation of Raw *IHV* for stations at different geographic longitudes; southern hemisphere stations: reddish color. Upper curves (left-hand scale) for stations with longitude near those of the geomagnetic poles. Lower curves (right-hand scale) for stations with longitudes $\sim 90^\circ$ away from the poles. Filled symbols show observations (roughly spanning the 20th century using predecessor stations as needed), while open symbols show the variation calculated from the Svalgaard Function, $S(\Psi) = 1.175/(1 + 3\cos^2(\Psi))^{2/3}$, [O'Brien and McPherron, 2002; Svalgaard, 1977]. All values are normalized to the mean for the year and repeated for one year in the right-hand half of the Figure.

1. Introduction

[2] *Mursula et al.* [2011] (MTL11) noticed that the strongest geomagnetic activity during the short 16-year interval 1993-2008 occurred when the Earth was at southern heliographic latitudes in 1994 and at northern heliographic latitudes in 2003. These two observations are presented as evidence that there is an annual variation of solar wind speed at Earth, changing phase between the two cycles resulting in a predominance of high speed streams from the southern hemisphere during the late phase of cycle 22 and from the northern hemisphere during the late phase of cycle 23 (although the high geomagnetic activity in October 2003 originated from solar activity in the southern hemisphere), and that this alternation is characteristic of solar cycles in general, providing long-term predictability of activity. The phase of the purported effect is such that the Earth experiences the fastest solar wind when it is north of the solar equator during positive polarity epochs (magnetic field positive (outward) at the northern pole of the Sun) such as during the decline of sunspot cycle 22 from 1990-1996 and when it is south of the solar equator during negative polarity epochs such as the decline of sunspot cycle 23 (2000-2008). MTL11 suggest a novel variation on the axial mechanism, namely that this purported 22-year variation in solar wind activity, coupled with the variation in heliographic latitude of the Earth during the year (between -7° in March and $+7^\circ$ in September), gives rise to an annual variation of geomagnetic activity with opposite phases between the declining phases of the cycles, and that these two annual waves when averaged over several cycles result in an apparent semiannual variation. They conclude that the observed semiannual variation is seriously overestimated and is largely an artifact of a 22-year variation. We examine this claim using the full geomagnetic record extending back well into the 19th century and find it unjustified.

2. The Semiannual and Universal Time Variations

[3] As MTL11 point out, the semiannual variation is a problem of long standing [Mairan, 1733; Broun, 1848; Bartels, 1932; McIntosh, 1959; Cliver et al., 2000]. Several hypotheses have been proposed over the years to account for the semiannual variation. These fall in four broad categories. 1: The 'Axial' hypothesis invoking driving forces varying with the heliographic latitude of the Earth; 2: The 'Equinoctial' hypothesis asserting that activity is modulated by a process sensitive to the angle between the geomagnetic dipole and the direction to the Sun; 3: The 'Russell-McPerron' hypothesis leading to enhanced southward heliospheric magnetic field, and hence enhanced reconnection, in April and October; and 4: Lack of 'Solar Illumination' of one polar ionosphere at each solstice, reducing geomagnetic activity. The mechanisms fall into two classes: 'Excitation', where the controlling parameter directly 'produces' geomagnetic activity (hypotheses 1 and 3), and 'Modulation', where

the parameter plays a role in modulating existing activity (hypotheses 2 and 4). It is likely that several of the mechanisms proposed will be operating at the same time to different degrees, slightly distorting the dominant signal. The hypotheses predict very different Universal Time variations of the activity, in particular, there would be no UT-variation for the Axial hypothesis. The Russell-McPerron mechanism is very effective in generating geomagnetic activity, but as shown by *Berthelier* [1976] and *Svalgaard* [1977] produces very little combined semiannual variation for equal amounts of heliospheric magnetic polarities.

[4] Geomagnetic activity is a very complicated phenomenon. To reduce the complexity we commonly resort to study geomagnetic indices instead. Many indices exist (Ci, u, Dst, AE, IL, ap, aa, am, IHV, etc), e.g. *Menvielle et al.* [2011]. When Julius Bartels designed the geomagnetic activity index Kp [Bartels et al., 1939; Bartels, 1949], he found that the K indices for each station had such a strong dependence on local time that the very non-uniform longitudinal distribution of the Kp stations precluded any investigations of the expected Universal Time (UT) of the activity as the angle, Ψ , between the direction to the Sun and the Earth's magnetic dipole varies both with day of year and with hour of universal time, thus introducing different semiannual variations depending on Universal Time. Thus it was necessary

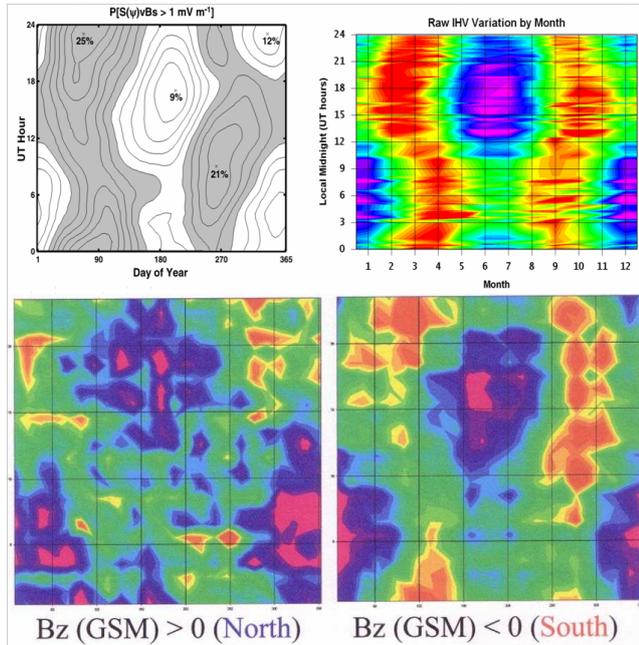


Figure 2. Month of year (abscissa) and UT (ordinate) variations of geomagnetic activity. Upper left: Probability of Ring Current injection [O'Brien and McPherron, 2002]. Upper right: Variation of “raw” IHV [Svalgaard and Cliver, 2007] for the ≈ 60 stations used to calculate IHV. Warm (red) colors signify maxima and cold (purple) colors minima. IHV measures geomagnetic activity for an interval around local midnight where the contribution (or interference) from the regular diurnal Sq variation is minimal. Lower panel: The variation of am index reduced for the influence of IMF strength and solar wind speed for the interval 1963-2003 for all times where we have simultaneous am , B , and V data, from *Svalgaard and Schulz* [2004], showing that the existence of the ‘hour-glass’ structure does not depend on the GSM orientation of the IMF (northward, left; or southward, right).

to remove the local time variation by applying normalization factors for each station for each month. The resulting Kp index should then have no UT variation at all, while still allowing for the semiannual variation. The ap index derived by linearizing Kp is therefore, by design, not suitable for a comprehensive study of the combined semiannual-UT variation of geomagnetic activity. Figure 1 shows how

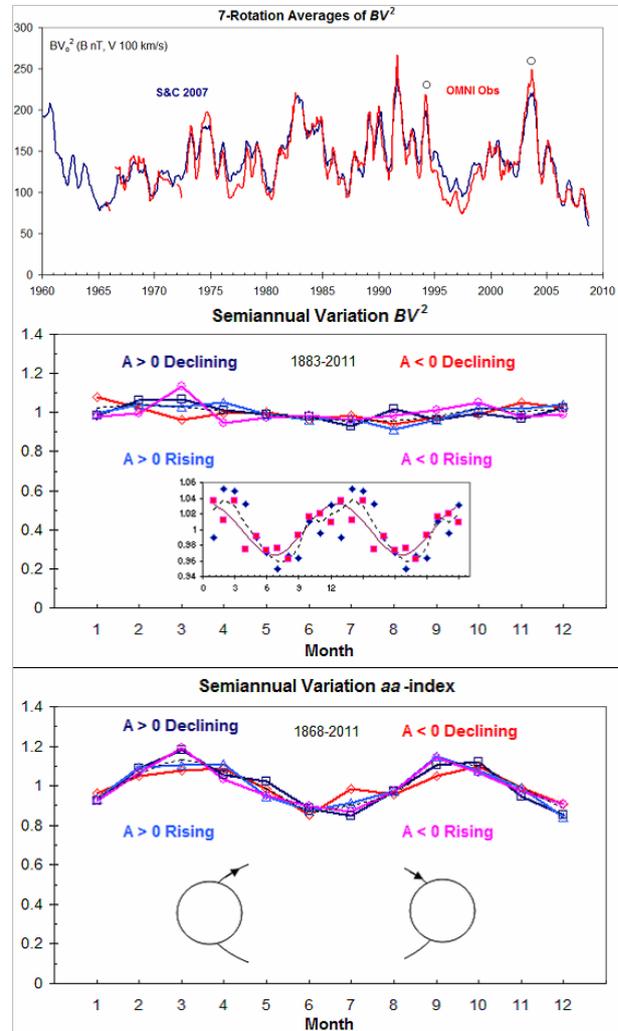


Figure 3. Upper: Seven-rotation running means of BV^2 (B in nT and V in units of 100 km/s) calculated from the IHV-IDV indices, [Svalgaard and Cliver, 2007, 2010] blue curve, and determined from in situ observed solar wind near the Earth (OMNI: <http://omniweb.gsfc.nasa.gov> red curve). Circles mark the high-speed streams in 1994 and 2003 that seemed so important to MTL11. Only rotations with better than 50% coverage were included in the calculation. Middle: Variation of the solar wind driver BV^2 through the year, normalized to mean values. Bluish colors for North Pole positive ($A > 0$; dark blue, squares: declining phase; light blue, triangles: rising phase), reddish colors for negative ($A < 0$; red, diamonds: declining; pink, circles: rising). Dashed black curve: all data. Insert: variation of normalized BV^2 (blue symbols: $A > 0$; red symbols: $A < 0$; dashed line: all data; full purple curve: the inverse square of the solar distance in AU). Lower: Variation of aa index; same symbols and colors as for the upper plot.

strongly the UT-variation modulates the semiannual variations at individual stations, using the ‘raw’ *IHV* index for each station [Svalgaard and Cliver, 2007]. The InterHourly Variation *IHV* measures geomagnetic activity for an interval around local midnight where the contribution (or interference) from the diurnal *Sq* variation is minimal, as the sum of the unsigned differences of the Horizontal Component from one hourly average to the next. Calculating the curves in Figure 1 using local nighttime ‘raw’ *K* indices (converted to amplitudes), rather than *IHV* yields identical results, as expected, because both indices respond the same way to the same physical processes. Apart from being expressed in units of the mean for the year, the ‘raw’ *IHV* has not been further processed in any way, so any variation with longitude has not been purposely removed.

[5] *Mayaud* [1967, 1970] utilized a more uniform distribution of geomagnetic observatories in both hemispheres to construct a true planetary activity index, *Km*, and its linear version *am*. Following Svalgaard [1977], Cliver et al. [2000] plotted the *am* index as 2D-contours as a function of month of year and of universal time, to reveal a characteristic ‘hourglass’ structure. The probability of injection of energy into the ring current [O’Brien and McPherron, 2002] and the ‘raw’ *IHV* index [Svalgaard and Cliver, 2007] display, (upper panel of Figure 2), the same characteristic hourglass structure, showing that the semiannual/UT variation is not just an artifact of the *am* index. New indices based on the same principles produce the same hourglass signature, e.g. Figure 3 of Finch et al. [2008]. Importantly, they show that for the last 50 years, a time when the 22-year solar wind-variability claimed by MTL11 to be particularly well-defined, geomagnetic indices show the clear imprint of the equinoctial hypothesis for the semiannual variation of geomagnetic activity, [Bartels, 1932; McIntosh, 1959; Svalgaard, 1977; Cliver et al., 2000], rather than the absence of the UT-variation one would expect to see if the axial effect invoked by MTL11 were the dominant cause of the semiannual variation. It is not the purpose here to discuss the

physics or causes of the various mechanisms of the semiannual variation, but to only point out that the variation actually *observed* is in close quantitative agreement with an equinoctial hypothesis and that therefore all other proposed causes with a substantially different UT-variation are not supported by the observations and can only be accommodated as small, second-order effects, but as such are undoubtedly present. As for the direct test of the MTL11 claim described below, which of the semiannual variation hypothesis one adheres to does not enter into the analysis at all.

3. Solar Wind Drivers

[6] Svalgaard [1977] (see also Crooker et al. [1977] and Murayama [1982]) have shown that the *am* index can with good approximation be calculated as $am = k q(\alpha, DOY, UT) BV^2$ where *k* is a scale factor, *q* is a geometrical factor depending on the IMF clock angle (α), on day of year (*DOY*), and on Universal time (*UT*), *B* is the magnitude of the IMF strength, and *V* is the solar wind speed, all at Earth. To separate to first order the geometric effects from the intrinsic variations of the solar wind *B* and *V*, we can divide the geomagnetic activity index under investigation by the product BV^2 . The lower panel of Figure 2 shows the resulting ‘hourglass’ observed for both northward and southward IMF. It is clear that the semiannual variation is closely regulated by the dipole tilt towards the solar wind, regardless of *B* and *V* and orientation of the IMF.

[7] The semiannual/UT variation is a *permanent* feature of the interaction between the solar wind and the magnetosphere, its functional form independent of the direction and strength of the IMF and of the speed of the solar wind, that is: The dominant semiannual-UT variation is a *modulation* of activity generated by the impact of the solar wind, as has been known for decades [Mayaud, 1977; Svalgaard, 1977]. The notion, put forward in MTL11 and elsewhere [Karinen and Mursula, 2006; Love and Gannon, 2009], that the semiannual variation is ‘excessive’, an artifact, due to uneven station distribution, incomplete removal of the regular diurnal *Sq* variation, or other deficiencies in deriving geomagnetic indices, is contradicted by the regularity of the combined semiannual-UT variation observed at stations of every longitude, for all solar wind conditions, for different indices, as well as for related geophysical phenomena [Mairan, 1733; Baker et al., 1999].

4. Annual Variation of Solar Wind Parameters

[8] Svalgaard and Cliver [2007, 2010] show how both *B* and *V* can be determined from the geomagnetic record (the *IDV* and *IHV* indices). The upper panel of Figure 3 shows 7-rotation running averages of the product BV^2 comparing the value reconstructed from geomagnetic activity directly with in situ observations, covering the whole of the space age. It is clear that the reconstructed values are a good representation of the physical reality when several rotations are averaged (for individual rotations the assumption of balanced northward and southward fields occasionally breaks down). MTL11 suggest that the phase of the annual variation of solar wind speed and geomagnetic activity changes systematically from one solar cycle to another, that the annual variation is largest in the declining phase of solar cycles, and that annual maxima are located in March during positive polarity periods and in September during negative polarity periods.

[9] As shown by Svalgaard and Cliver [2007] there is a true, but small (5%), second order, variation of geomagnetic activity caused by the variation of *B* with distance to

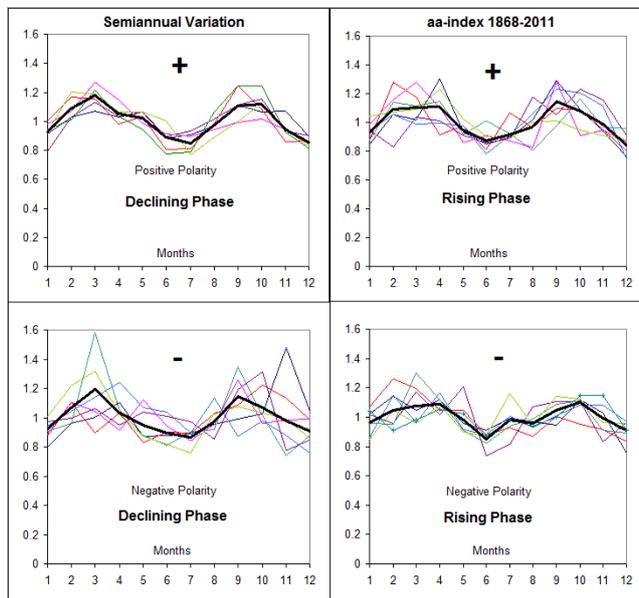


Figure 4. Variation of the *aa* index (1868-2011) separately for the declining and rising phases of each solar cycle and for each polarity, positive or negative, normalized to the average for each section. The thick, black curve shows the average variation, while thin, colored curves are for individual solar cycles.

the Sun, as expected (their Figure A7 and the insert in the middle panel of Figure 3). This small variation, attesting to the validity of the reconstructed solar wind parameters, is, of course, independent of the polarities of the solar cycles, as the orbit of the Earth does not change with the cycles, and is not in phase with the variations claimed by MTL11. In addition, at any time, the solar wind can have enhancements of some duration, especially in V as were the cases for the high-speed streams of 1994 and 2003, or in HMF-polarity anomalies as in 1954 and 1996, e.g. *Cliver et al.* [2004].

[10] The central thesis of MTL11's mechanism for the semiannual variation can be stated as follows: The observed solar drivers, the excitation parameters B and V , do not vary randomly with respect to the Earth's orbit and their variation, when coupled with the axial effect, is of sufficient amplitude to be the dominant cause of the observed semiannual variation. We can put this thesis to a direct test using as our measures of the solar driver and of geomagnetic activity the long-term variation of BV^2 (directly observed since 1965 and reconstructed from IDV and IHV before that) and of the aa index (which is adequate for monthly values). We consider four subsets of the series: rising and declining phases of the cycle and for each of those, positive and negative polarity (of the northern pole, often denoted as $A > 0$), and then calculate the variations of BV^2 and of aa as a function of month of year. The data for this calculation is given in the electronic supplement. It is plain from the resulting Figure 3 that during the declining phase there is no asymmetry in solar wind parameters nor in geomagnetic activity between the first half of the year and the second half, contrary to the claims of MTL11. For the rising phase, there is no asymmetry either. The claims thus fail this direct test.

[11] As average curves at times may conceal actual variation, we show in Figure 4 for individual cycles since 1868 that there is no systematic annual variation in the aa index, neither for the declining phase or the rising phase, nor for either polarity. To compare cycles, the values for each section of a cycle were normalized by the average for that section. A recent study of the Dst index for 1962-1998 also shows no dependency of the semiannual variation on the sign of the solar polar fields [*Oh and Yi*, 2011].

5. The 22-year Variation

[12] *Chernosky* [1966] discovered a 22-year variation in geomagnetic activity. The effect is explained [*Russell*, 1975; *Svalgaard*, 1977] by a combination of the Rosenberg-Coleman effect [*Rosenberg and Coleman*, 1969; *Wilcox and Scherrer*, 1972] varying the dominant polarity of the heliospheric magnetic field and the Russell-McPherron effect [*Russell and McPherron*, 1973], favoring enhanced geomagnetic activity when the solar and terrestrial magnetic dipoles have opposite directions [*Cliver et al.*, 2004]. This is a purely geometrical effect, not dependent on any inherent hemispheric asymmetries in solar activity. This (real) 22-year cycle is very distinct from and has nothing to do with the variation of solar wind speed claimed by MTL11.

6. Conclusion

[13] MTL11 make two claims 1: that northern and southern solar hemispheres have a 22-year cycle in systematically different, and opposite, activity levels resulting in corresponding variations of the solar drivers of geomagnetic activity, primarily solar wind speed. When the Earth is north (south) of the solar equator, a more active northern (southern) hemisphere would result in a stronger and faster solar

wind causing enhanced geomagnetic activity, and 2: that the well-established semiannual variation is largely an axial effect resulting from the above asymmetry, averaging two disparate annual variations offset by six months resulting in an artificial semiannual variation.

[14] We show here that there are no oppositely organized annual variations in the solar driver of geomagnetic activity nor in the observed activity in step with the alternating cycle polarities, precluding long-term predictive capability. Finally, such a purely axial mechanism does not allow for the UT variation which is a well-established and integral part of the phenomenon. Consequently, the semiannual variation is not 'seriously overestimated' and is not in need of revision.

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