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Long-term variation of the semiannual amplitude in the aa index

Ana G. Elias [a,b], Virginia M. Silbergleit [a,c,*], Alicia L. Clua de Gonzalez [d]

[a] Consejo Nacional de Investigaciones Científicas y Técnicas, CONICET, Argentina
[b] Departamento de Física, Facultad de Ciencias Exactas y Tecnología, Universidad Nacional de Tucuman, Avenida Independencia 1800, 4000 Tucuman, Argentina
[c] INTECIN, Facultad de Ingeniería, Universidad Nacional de Buenos Aires, FIUBA, Avenida Paseo Colon 850-CABA, 1043 Buenos Aires, Argentina
[d] Divisão de Geofísica Espacial, Instituto Nacional de Pesquisas Espaciais, Avenida dos Astronautas, 1758, Jardim da Granja, 12227010, P.O. Box 515, São José dos Campos, São Paulo, Brazil

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ABSTRACT

The long-term variation of the semiannual amplitude in the geomagnetic activity index aa is analyzed with the purpose of contributing to the understanding of solar variability, directly linked to geomagnetic variability. The time series of the semiannual oscillation amplitude, obtained through a wavelet analysis of the daily aa series, presents a long-term variation similar to that shown by solar and geomagnetic indices, like aa itself or Dst. However, the maximum in the semiannual amplitude series occurs around 1947, almost 10 years before it occurs in solar and geomagnetic indices time series. The phase of the semiannual oscillation fluctuates around the values predicted by the equinoctial and Russell–McPherron models, with a predominance of the equinoctial mechanism during the period of maximum semiannual amplitude. A possible source of changes in the equinoctial mechanism would be the secular variation of the Earth's dipole tilt. But, since it does not follow the semiannual amplitude trend, at first sight, it seems not to be responsible for the equinoctial predominance around 1947. The analysis of quiet and disturbed days separately indicates that only disturbed days present the semiannual annual amplitude maximum around 1947, so the 10 year time shift could be due to the mechanism responsible for the semiannual variation in geomagnetically active periods.

1. Introduction

The study of periodicities in solar data has long been of interest, being fundamental for understanding the mechanisms of solar variability and solar–terrestrial relationships. In general, frequency and amplitude of solar periodicities are not constant in time, that is solar and geomagnetic activity parameters present non-stationary oscillations. There are many studies dealing with trends in geomagnetic indices (Demetrescu and Dobrica, 2008; Rouillard et al., 2007; Cliver et al., 2002; Vennerstrom, 2000; to mention a few) but not so many dealing with trends in amplitude and phase of the known oscillations in solar and geomagnetic activity parameters. Among the latter, Le Mouel et al. (2004a, b) have analyzed the 6-month line amplitude of the aa index and obtained a long-term variation that they found similar to the long-term variation of various solar and magnetic parameters.

The well known semiannual variation in geomagnetic activity with maxima near equinoxes is not attributed to a conclusive origin but generally to one or more of the three following principal sources:

(1) The axial hypothesis caused by the annual variation of the heliographic latitude of the Earth, Bo (Cortie, 1912): the Sun's equator is inclined at an angle of about 7.3° with respect to the ecliptic (plane of the Earth's orbit), so Bo, which is the latitude of the Earth referred to the solar equator in degrees, varies with the epoch of the year. The two planes intersect at two points, which the Earth passes on about 5 June and 5 December (Julian days 156 and 339, respectively). On these dates the Earth is in the plane of the Sun's equator and Bo becomes nearly zero. On about 5 March and 5 September (Julian days 64 and 248, respectively) the Earth is at its maximum angular distance from the solar equatorial plane ($Bo = \pm 7.3°$) and thus more closely aligned with active regions and mid-latitude coronal holes. The time variation of the geomagnetic effect follows the minus cosine of Bo (black line in Fig. 1), so, the cosine has its maximum value when $Bo=0$ corresponding to the Earth aligned with the Sun's equator. Evidences of this mechanism were shown by Priester and Cattani (1962); and more recently, but acting with the contribution of the other two mechanisms described ahead, by Cliver et al. (2004) for example.

* Corresponding author at:INTECIN, Facultad de Ingeniería, Universidad Nacional de Buenos Aires, FIUBA, Avenida Paseo Colon 850-CABA, 1043 Buenos Aires, Argentina.
E-mail address: vms10ar@yahoo.com.ar (V.M. Silbergleit).

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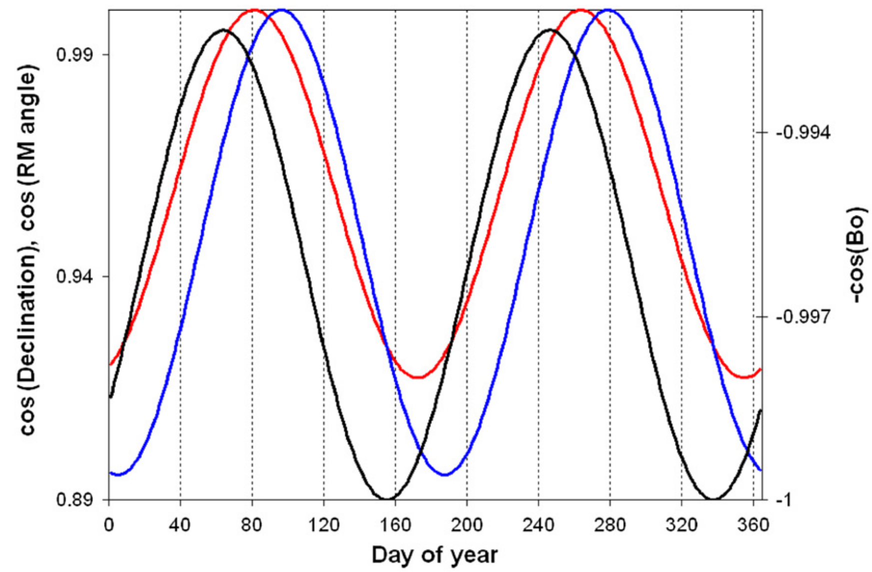

Fig. 1. Cosine of the heliographic latitude of the Earth, Bo, (black line), cosine of the declination (red line), and cosine of the sum Bo+declination (blue line), which represent the time variation of the effect on geomagnetic activity of the axial, equinoctial, and Russell–McPherron mechanisms, respectively, with the pair of maxima during 5 March–5 September, 21 March–21 September, and 5 April–8 October for each mechanism. Note: Bo was obtained from the Astronomical Almanac 2009 (available at http://asa.usno.navy.mil). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

(2) The equinoctial hypothesis caused by the annual variation of the orientation of the Earth's magnetic axis relative to the Earth–Sun line, ψ (Bartels, 1932; McIntosh, 1959; Svalgaard, 1977): geomagnetic activity maximizes at the equinoxes (March 21 and September 21, corresponding to Julian days 80 and 264, respectively) when the angle between these two orientations is 90° (declination$=0$) and the coupling efficiency with the magnetosphere should be maximum. Qualitatively, this is due to the Earth's magnetic field seen by the solar wind that is weakest when $\psi=90^\circ$ (Svalgaard, 1977). The seasonal variation of ψ follows the variation of the declination and its effect on geomagnetic activity follows the cosine of the declination angle (red line in Fig. 1).
(3) The Russell–McPherron mechanism (Russell and McPherron, 1973): the controlling parameter is the angle φ between the z-axis of the geocentric solar magnetospheric (GSM) coordinate system and the solar equatorial plane which can be obtained from the sum of Bo and ψ, so it depends on both, the tilts of Earth's dipole and the solar equatorial plane. It may be thought then as a combined axial and equinoctial hypothesis. When φ is minimum, which occurs on 5 April and on 8 October (Julian days 95 and 281 respectively), geomagnetic activity is expected to reach a maximum, because at these times a solar wind magnetic field lying entirely in the Sun's equatorial plane has its maximum projection on the z-axis of the GSM coordinate system. Magnetic reconnection between the solar wind magnetic field and the Earth's dipole field is expected then (Russell and McPherron, 1973; McPherron et al., 2009). As McPherron et al. (2009) wrote: "Reconnection drives internal flows in the magnetosphere and produces magnetospheric sub-storms responsible for geomagnetic activity." The expected seasonal variation in geomagnetic activity due to φ corresponds to that of the cosine of the sum of Bo and ψ (that behaves like the absolute value of the solar P-angle mentioned by Cliver et al. (2002) as the angle of the Russell–McPherron mechanism). In summing Bo to the effect of the Earth dipole tilt, the maxima are shifted from March 21 and September 21 to April 5 and October 8, respectively, as can be noticed in Fig. 1, where cos(Bo+declination) is depicted in blue.

Moreover, according to Clua de Gonzalez et al. (1993) these three mechanisms could be acting together. There is also another proposed cause, not analyzed here, that is solar illumination (Lyatsky et al., 2001; Newell et al., 2002).

In the present work, we analyze the long-term variation of the semiannual amplitude in the aa index, not only to contribute to the understanding of the mechanisms of solar variability, but also to the origin of the semiannual variation in geomagnetic activity.

2. Data analysis

Daily mean values of aa index provided by the National Geophysical Data Center (ftp://ftp.ngdc.noaa.gov) for the period January 1868–December 2006 were used. To study the time behavior of aa semiannual periodicity the wavelet power spectrum (WPS), which is commonly applied in geosciences, was calculated using the wavelet computational algorithm of Torrence and Compo (1998). The shape of the chosen wavelet function must present the general characteristics of the time series, which is being analyzed. If the time series presents abrupt variations, the Haar wavelet may be the most convenient, but if it has smoother variations, the Mexican Hat or the Morlet wavelet are more adequate. In our case, focused on amplitude changes, a complex smooth wavelet such as the Morlet wavelet is the most appropriate (Kumar and Foufoula-Georgiou, 1997), since it consists of a complex sine wave modulated by a Gaussian given by

$$\Psi_o(\eta) = \pi^{-1/4} e^{i\omega_o\eta} e^{\eta^2/2}$$

where η is a non-dimensional "time" parameter (related to the scale) and ω_o is a non-dimensional frequency. We have restricted our analysis to the period range 5–7 months, and according to our needs of time and frequency resolution we have chosen ω_o=20. The wavelet transform of the discrete time series aa(t) is assessed as

$$W_n(s) = \sum_{n'=0}^{N-1} \mathrm{aa}(t_{n'}) \Psi^* \left[\frac{(t_{n'} - t_n)}{s} \right]$$

where ψ^* is the complex conjugate of the normalized Morlet wavelet ψ_o, which is scaled (by varying the scale s) and translated (by t_n). The argument $(t_{n'}-t_n)/s$ corresponds to η, and N is the total number of data points, that is number of days in the period January 1, 1868–December 31, 2006 (=50769). The scale s (that is given in days in