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Letter

On the relationship between the aa index and tidal forces

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Abstract: A previously unknown relationship between the tidal forces and aa index is shown and used to discuss when the next maximum of the annual aa index is expected to occur.

Keywords: tidal forces; moon; sun; geomagnetic field

1. Introduction

It is well-known that solar activity affects the Earth, but only within the past two centuries did people realize that geomagnetic storms, presenting themselves through magnificent auroras, are caused by eruptions on the Sun. However, the relationship between solar activity and geomagnetic storms is not straightforward; as Table 1 reveals, some solar activity generates powerful solar flares that do not translate into powerful geomagnetic storms, while some geomagnetic storms follow rather puny solar flares. Nor is there a simple correspondence between coronal mass ejections and geomagnetic storms. Some authors, e.g. [1, 2], and references therein, suggested that the Earth's magnetic field is affected by the tidal forces created by the Moon and Sun; their view was echoed by several websites, e.g. [3, 4]. There have been attempts to predict upcoming maxima of geomagnetic indices based on the previous maxima and sunspot numbers, e.g. [5, 6]. Most, if not all, authors considering the relationship between the tidal forces and geomagnetic activity discuss the proximity of geomagnetic events to different phases of the Moon. In this article we consider the annual aa index, defined at [7], as a proxy for the background geomagnetic field with short-term geomagnetic variations smoothed out. We will show that the maxima of the annual aa index occur at the time when New/Full Moon is augmented by a close perigee, a close lunar node, or a close perihelion; it is the confluence of two or more of these factors that seems to determine the maxima of the annual aa index.

Table 1. Most powerful solar flares and geomagnetic storms. Not all powerful solar flares are associated with powerful geomagnetic storms, and not all powerful geomagnetic storms are associated with powerful solar flares. Plenty is known about the post-1996 solar flares and geomagnetic storms, considerably less is known about the 1976–1995 ones, while the data about the pre-1976 solar flares and geomagnetic storms is incomplete and rather spotty.

Complete data is only available since 1996				
All $\geqslant X4.1$ solar flares in 1996 – 2021, [8]		All geomagnetic storms with Kp $\geqslant$ 8 in 1996 – 2021, [9]		
2017/9/10	X8.2			
2017/9/6	X9.3	**2017/9/8**	Kp=8+	Ap=1065
		2015/6/22	Kp=8+	Ap=575
		two-year gap		
2014/2/25	X4.9			
		two-year gap		
2012/3/7	X5.4	**2012/3/9**	Kp=8	Ap=87
2011/8/9	X6.9			
2006/12/6	X6.5	2006/12/15	Kp=8+	Ap=94
2006/12/5	X9.0			
2005/9/9	X6.2			
2005/9/8	X5.4			
2005/9/7	X17.0			
		2005/8/24	Kp=9-	Ap=102
		2005/5/15	Kp=8+	Ap=87
		2005/5/8	Kp=8+	Ap=91
2005/1/20	X7.1	**2005/1/21**	Kp=8	Ap=66
		2004/11/10	Kp=9-	Ap=161
		2004/11/9	Kp=9-	Ap=119
		2004/11/8	Kp=9-	Ap=140
		2004/11/7	Kp=8	Ap=50
		2004/7/27	Kp=9-	Ap=186
		2004/7/25	Kp=8	Ap=154
2003/11/4 (est)	X28	2003/11/20	Kp=9-	Ap=150
2003/11/2	X8.3	2003/10/31	Kp=8+	Ap=116
2003/10/29	X10.0	**2003/10/30**	Kp=9	Ap=191
2003/10/28	X17.2	**2003/10/29**	Kp=9	Ap=204
2003/10/23	X5.4			
		2003/5/29	Kp=8+	Ap=109
2002/7/23	X4.8			
		2002/5/23	Kp=8+	Ap=78
2001/12/13	X6.2	2001/11/24	Kp=8+	Ap=106
		2001/11/6	Kp=9-	Ap=142
2001/8/25	X5.3			
2001/4/15	X14.4			
2001/4/6	X5.6	2001/4/11	Kp=8+	Ap=85
2001/4/2	X20.0			
		2001/3/31	Kp=9-	Ap=192
		2000/9/17	Kp=8+	Ap=56
2000/7/14	X5.7	**2000/7/15**	Kp=9	Ap=164
		2000/5/24	Kp=8	Ap=98
		2000/4/7	Kp=9-	Ap=74
		2000/4/6	Kp=8+	Ap=82
		1999/10/22	Kp=8	Ap=91
		1999/9/22	Kp=8	Ap=50
		1998/8/27	Kp=8	Ap=144
1998/8/18	X4.9	1998/8/25	Kp=8+	Ap=117
		1998/5/4	Kp=9-	Ap=101
1997/11/6	X9.4			

Less data is available for 1976 – 1995, whatever is available is shown below		
All $\geqslant X9.0$ solar flares in 1976 – 1995, [8]		Most powerful geomagnetic storms in 1976 – 1995, [9]
		1995/4/7
		1994/4/17
1992/11/2	X9.0	
		1991/11/8
1991/6/15	X12.0	
1991/6/11	X12.0	
1991/6/9	X10.0	
1991/6/6	X12.0	
1991/6/4	X12.0	
1991/6/1	X12.0	
1991/1/25	X10.0	
1990/5/24	X9.3	
1989/10/19	X13.0	
1989/9/29	X9.8	
1989/8/16	X20.0	**1989/8/16**
1989/3/10	X15.0	**1989/3/13**
five-year gap		
1984/5/20	X10.1	
1984/4/24	X13.0	
1982/12/17	X10.1	
1982/12/15	X12.9	
1982/7/9	X9.8	
1982/6/6	X12.0	
four-year gap		
1978/7/11	X15.0	

2. Discussion

Let us first start with a few definitions. New/Full Moon recurs on average every 29.530588 days, while the perigees recur on average every 27.55455 days; and, since

$29.530588 \times 14 \approx 413.428$, $27.55455 \times 15 \approx 413.318$, the 413-day time interval is considered as the average common period of New/Full Moon and perigee. As [10] reveals, on average every 413 days New/Full Moon comes within 11 hours of a perigee. As usually, we will use *syzygy* to denote either New or Full Moon, and *syzygy-perigee* to denote a pair of a syzygy and a perigee separated by $\leqslant 11$ hours. Although the average time between two adjacent New Moon-perigees or two adjacent Full Moon-perigees is close to 413 days, the exact number of days varies. We further define the *spread of a syzygy-perigee* to be the time between the syzygy and perigee in the syzygy-perigee. A syzygy-perigee is said to be *synchronized within 140 minutes*, or for the purpose of this article simply *synchronized*, if its spread is $\leqslant$ 140 minutes. A series of several consecutive synchronized syzygy-perigees will be referred to as a *140-minute synchronization period*, or for the purpose of this article simply *synchronization period*, due to the synchronized appearance of perigees and syzygies. The *core syzygy-perigee*, or simply the *core*, of a synchronization period is the syzygy-perigee with the smallest spread. All other things being equal, the tidal force should increase during synchronization periods, reaching its maxima near the core. However, "other things" are never equal. One of the most obvious things affecting the tidal force other than syzygies and perigees, is the Earth-Moon-Sun alignment; the closer to a straight line is the alignment, the stronger is the tidal force. Thus a non-core syzygy-perigee close to an eclipse, or even a lunar node, may exert a stronger tidal force than a core syzygy-perigee removed from lunar nodes.

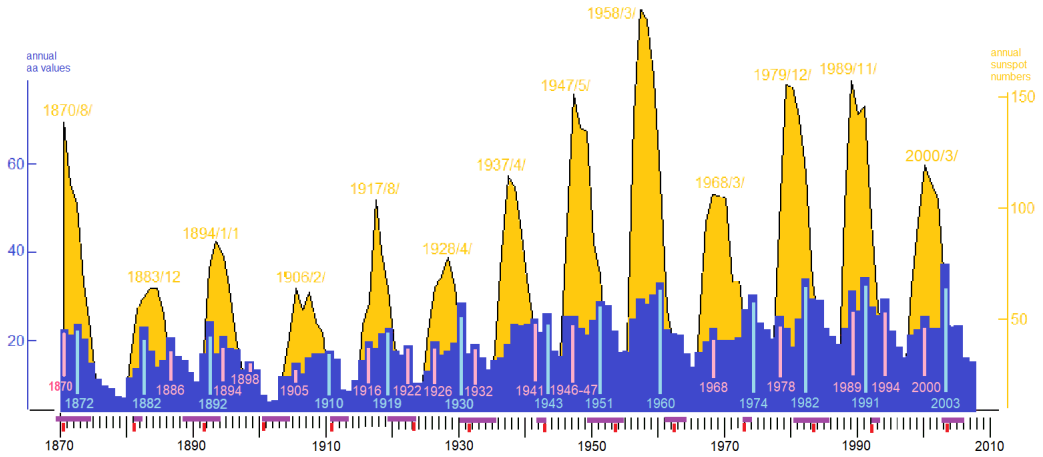

Figure 1. Sunspot numbers in yellow and annual aa index in blue, [11]. The maxima of the annual aa index in each solar cycle are marked by blue vertical lines and labeled by years; they will be referred to simply as *primary aa maxima*, or simply *aa maxima*. *Secondary aa maxima* are the maxima marked by pink lines. Purple horizontal intervals and red markers approximately mark, correspondingly, the 140-minute synchronization periods and core syzygy-perigees of Table 2.

Figure 1 compares the annual aa index, as a measure of the Earth's magnetic field, to sunspot numbers (SSN), as a measure of solar activity. Although the aa index overall follows the solar activity, the aa maxima seem to appear rather randomly relative to the SSN maxima. However, that is not the case. The 1870–2007 portion of Table 2 reveals that all aa maxima in 1870–2007 occurred within a year of a synchronization period. We may test the hypothesis on the 2007–2020 period, following the period of Figure 1. Indeed, the graph of the aa index in 2007–2020 available in [6, 12] shows that the maximum of the annual aa index is attained in 2015 which, as Table 2 shows, was inside the

2011/3/19–2016/11/14 synchronization period. Twelve calendar years of the 14 annual aa maxima in Table 2 contained a synchronized syzygy-perigee, while two calendar years of annual aa maxima (1991, 1960) were ⩽ 20 days away from a synchronized syzygy-perigee. What are the chances of that? Of the 152 years 281 days ≈152.8 calendar years in 1869/2/26–2021/12/4, approximately 83.8 years, or ≈ 55%, fall within a year of a synchronization period and ≈ 69 years, or ≈ 45%, are more than a year away from a synchronization period; one would expect at least some of the annual aa maxima to occur more than a year away from the synchronization periods but none did.

Table 2. Fifteen synchronization periods of 1869–2020, constructed using [10]. The first two columns show synchronized syzygy-perigees with their spreads, grouped into synchronization periods; the lines between consecutive synchronization periods show the time between them. The third column shows events that may augment the tidal force. The fourth column indicates by words New and Full whether the synchronization period comprises New Moon-perigees or Full Moon-perigees and the length of the synchronization period. The fifth column shows the years of aa maxima. The 2011/3/19–2016/11/14 does not appear in Figure 1 and was added based on recent data, e.g. [12].

synchronized syzygy-perigees	sp re ad	nearby eclipse, lunar node, perihelion	New/ Full& length	aa max-ima
2030/5/17	137	next synchronized syzygy-perigee		
2024/3/10 – 2030/5/17 = 6 years 68 days				
2024/3/10	116		New	up-
2023/1/21	4	2023/1/4 perihelion	2 y	com
2021/12/4	137	2921/12/3 eclipse	97 d	ing
2015/9/28 – 2021/12/4 = 6 years 67 days				
2015/9/28	65	2015/9/27 eclipse		**2015**
2014/8/10	27		Full	
2013/6/23	23		4 y	
2012/5/6	2	2012/5/7 lunar node	193 d	
2011/3/19	59			
2005/1/10-2011/3/19 = 6 years 68 days				
2005/1/10	116	2005/1/2 perihelion	New	
2003/11/23	15	2003/11/23 eclipse	2 y	2003
2002/10/6	120		96 d	
1993/3/8 – 2002/10/6 = 9 years 212 days				
1993/3/8	71		Full	
1992/1/19	58	1992/1/18 lunar node	1 y	
(1991/7/11 was New Moon-perigee & eclipse)			48 d	1991
1985/11/12 – 1992/1/19 = 6 years 68 days				
1985/11/12	110	1985/11/11 eclipse		
1984/9/25	20		New	
1983/8/8	13		5 y	
1982/6/21	17	1982/6/22 eclipse	241 d	1982
1981/5/4	32			
1980/3/16	93	1980/3/14 lunar node		
1974/1/8 – 1980/3/16 = 6 years 67 days				
1974/1/8	76	1974/1/7 lunar node	Full	1974
		1974/1/4 perihelion	1 y	
1972/11/20-21	55		49 d	
1963/4/23 – 1972/11/20 = 9 years 213 days				
1963/4/23	116		New	
1962/3/6	39	1962/3/4 lunar node	2 y	
1961/1/16	89	1961/1/2 perihelion	96 d	1960
1954/11/10 – 1961/1/16 = 6 years 67 days				
1954/11/10	70			
1953/9/23	13		Full	
1952/8/5	51	1952/8/6 eclipse	5 y	
1951/6/19	55		241 d	1951
1950/5/2	72			
1949/3/14	140	1949/3/16 lunar node		
1943/1/6 – 1949/3/14 = 6 years 67 days				
1943/1/6	30	1943/1/2 perihelion	1 y	1943
1941/11/19	98		48 d	
1935/9/12 – 1941/11/19 = 6 years 68 days				
1935/9/12	130			
1934/7/26	104	1934/7/26 eclipse	Full	
1933/6/8	99		5 y	
1932/4/20	76		241 d	
1931/3/4	11	1931/3/6 lunar node		
1930/1/14 -15	124	1930/1/3 perihelion		1930
1923/11/8-1930/1/14 = 6 years 67 days				
1923/11/8	27			
1922/9/21	60	1922/9/21 eclipse	New	
1921/8/3	79		4 y	
1920/6/16	87		192 d	
1919/4/30	107	1919/5/1 lunar node		**1919**
1913/2/21 – 1919/4/30 = 6 years 68 days				
1913/2/21	117		Full	
1912/1/4	5	1912/1/3 perihelion	2 y	
1910/11/17	131	1910/11/16 eclipse	96 d	1910
1904/9/9-1910/11/17 = 6 years 69 days				
1904/9/9	87	1904/9/9 eclipse		n
1903/7/24	69		New	o
1902/6/6	73		4 y	n
1901/4/18	41	1901/4/20 lunar node	192 d	e
1900/3/1	40			
1893/12/23 – 1900/3/1 = 6 years 68 days				
1893/12/23	114	1894/1/1 perihelion		
1892/11/4	4	1892/11/4 eclipse	Full	1892
1891/9/18	87		5 y	
1890/7/31	119		241 d	
1889/6/13	128	1889/6/14 lunar node		
1882/2/18 – 1889/6/13 = 7 years 115 days				
1882/2/18	86		New	1882
1880/12/31	44	1880/12/30 eclipse	1 y	
		1881/1/1 perihelion	49 d	
1874/10/25 – 1880/12/31 = 6 years 67 days				
1874/10/25	126	1874/10/24 eclipse		
1873/9/6	56		Full	
1872/7/20	36		5 y	1872
1871/6/3	28	1871/6/4 lunar node	241 d	
1870/4/15	6			
1869/2/26	84	1869/2/25 lunar node		

Table 3. Pairing secondary maxima of Figure 1 to syzygies, perigees, and eclipses, constructed using [10]. In **bold** are the secondary maxima that do not contain a triplet of simultaneous syzygy, perigee, and eclipse; all of them were close to solar maxima.

secondary aa maxima	same year lunar events increasing tidal force
2012, see [12]	2012/6/3 perigee, 2012/6/3 eclipse, 2012/6/4 Full Moon; 2012/11/14 perigee, 2012/11/14 eclipse, 2012/11/13 New Moon
2000	2000/7/1 New Moon-perigee, 2000/7/2 eclipse; 2000/7/30 New Moon, 2000/7/30 perigee, 2000/7/30 eclipse
1994	1994/11/3 New Moon-perigee, 1994/11/3 eclipse; 1994/5/24 perigee, 1994/5/24 eclipse, 1994/5/25 3:40 Full Moon;
1989	1988/8/27 Full Moon-perigee, 1988/8/28 2:13 eclipse; 1989/3/6 22:50 eclipse, 1989/3/7 New Moon, 1989/3/8 7:52 perigee; solar maximum, 1989 solar maximum
1978	close to 1979 solar maximum
1968	1967/11/2 1:48 - 5:49 New Moon-perigee, 1967/11/1 eclipse; 1968 solar maximum
1957	close to 1958 solar maximum
1946-1947	1946/12/9 0:12 perigee, 1946/12/8 Full Moon, 1946/12/8 eclipse; 1946/5/30 New Moon-perigee, 1946/5/31 eclipse; 1947 solar maximum
1941	1941/3/13 Full Moon, 1941/3/14 perigee, 1941/3/14 2:45 eclipse; 1941/11/19 synchronized New Moon-perigee
1932	1932/3/22 Full Moon, 1932/3/22 eclipse, 1932/3/23 perigee; 1932/4/20 synchronized Full Moon-perigee
1926	1926/1/14 New Moon, 1926/1/14 perigee, 1926/1/14 eclipse, 1926/1/2 perihelion
1922	1922/9/21 synchronized New Moon-perigee, 1922/9/21 eclipse; 1922/3/12 23:30 perigee, 1922/3/13 Full Moon, 1922/2/14 eclipse
1916	1916/7/15 Full Moon-perigee, 1916/7/15 eclipse; 1917/1/23 New Moon-perigee, 1917/1/22 eclipse; 1917 solar maximum
1905	1905/2/19 18:53 Full Moon, 1905/2/20 perigee, 1905/2/20 eclipse may be viewed as the aa maximum corresponding to the 1900/3/1 - 1904/9/9 synchronization period
1898	1898/7/3 Full Moon-perigee, 1898/7/4 6:23 eclipse; 1899/1/11 22:49 - 1899/1/12 1:38 New Moon-perigee, 1899/1/11 eclipse
1894	1893/12/23 synchronized Full Moon-perigee, the 2nd closest perigee of 1550 - 2050; 1894 solar maximum
1886	1886/8/29 New Moon-perigee, 1886/8/29 eclipse; 1886/2/18 Full Moon, 1986/2/18 perigee, 1886/2/19 eclipse
1870	1870 solar maximum, 1870/4/15 core syzygy-perigee

Table 2 reveals that not only all 14 aa maxima occurred within a year of a synchronization period, but also 10 of them (2003, 1943, 1892; 1991, 1982, 1974, 1960, 1930, 1910, 1882), or $\approx$ 71%, occurred either in the year of a core syzygy-perigee, or the year before, or they year after; such years make up $\approx \frac{3\times15}{2020-1868} \approx 30\%$ of all years. The 1951 and 1872 aa maxima were $\approx$ 2 years from the, correspondingly, 1952/8/5 and 1870/4/15 core syzygy-perigees; yet the secondary aa maxima of 1952 and 1870 were of almost the same value as the 1951 and 1872 aa maxima and within a year of the 1952/8/5 and 1870/4/15 core syzygy-perigees. Only the 2015 and 1919 aa maxima were removed from corresponding core syzygy-perigees by $\geqslant$ 2 years; again the secondary aa maxima of 2012 and 1922 were within a year of the, correspondingly, 2012/5/6 and 1923/11/8 core syzygy-perigees.

We conclude that the aa maximum during a solar cycle is determined not just by SSN but also by the tidal force during the solar cycle, and the tidal force appears to be more important in creating the annual aa maximum of a given solar cycle than SSN.

The maxima of the smoothed monthly mean given in Figure 1 of [6] also fall within a year of the corresponding synchronization periods from 1868 onwards.

Other than primary aa maxima, Figure 1 also shows secondary maxima marked by pink lines. Table 3 shows that all but three of the secondary maxima coincided with the years containing

simultaneous syzygy, perigee, and eclipse; the three exceptions coincided with solar maxima. Notice that the 1894 secondary maximum was merely 8 days away from the 1893/12/23 synchronized Full Moon-perigee. The 1919 aa maximum is the aa maximum farthest removed from the core syzygy-perigee of the corresponding synchronization period; castling it with the 1922 secondary maximum would have eliminated this somewhat exceptional case.

Synchronization periods recur almost periodically, the average time between the cores of synchronization periods is $\approx 3,706$ days or ≈ 10.15 years, obtained by dividing 51,886 days between 1870/4/15 and 2012/5/6 by 14. The number is very close to the average time of 3,944 days, or ≈ 10.8 years, between solar maxima in Figure 1 obtained by dividing 47,329 days between 1870/8/15 and 2000/3/15 by 12. Although synchronization periods and solar cycles appear usually in tandem, occasionally there pops up an orphaned synchronization period unattached to a solar cycle, i. e. the 1900/3/1–1904/9/9 synchronization period which appeared between two solar cycles and did not produce an aa maximum. Yet, the 1900/3/1–1904/9/9 synchronization period produced a secondary aa maximum in 1905 and the 1903/10/31 powerful geomagnetic storm. All but one aa maxima in Figure 1 are well-defined, the only exception is the 1910 maximum, it is almost indistinguishable from the aa index in 1908–1909; it is as if the 1910/11/17–1913/2/21 synchronization period lost some might to its 1900/3/1–1904/9/9 predecessor.

3. Conclusions

Table 2 and Figure 1 show that all aa maxima occurred within a year of a synchronization period, and 12 out of 14 aa maxima occurred within 2 years of a core syzygy-perigee; it is hard to attribute this to a mere coincidence. Table 3 shows that all but three secondary aa maxima occurred in years when the tidal force was amplified by New/Full Moon, perigee, and eclipse coming together. We may infer that within a solar cycle the tidal force plays a significant role in the formation of primary and secondary aa maxima. We may speculate that first, the solar activity fills up the Van Allen Belts with energetic particles; and then, the tidal force generated by the Moon and Sun "shakes" the Van Allen Belts somewhat similarly to how one shakes a dried up Christmas tree. Just like the Christmas tree drops its needles when shaken, the Van Allen Belts disperse energetic particles. Of course, the tidal force is only one of several components determining the aa maxima, but it is certainly an important one.

The 2021/12/4–2024/3/10 synchronization period is upcoming; it is in the first half of solar cycle 25 that started in 2019. The aa annual maximum during solar cycle 25 is expected to occur either in 2021–2024 or, if solar cycle 25 is sufficiently long, or in 2029–2031; the most likely years of the annual aa maximum are 2022–2023. This is somewhat better than April 2025±32 months predicted in [6].

Conflict of interest

The author declares no conflict of interest.

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