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Predicting the maximum of 363-day smoothed highest 3-hourly aa index in 3-day-interval with the preceding minimum of 11-year cycle

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Abstract

Predicting the strength and peak time of geomagnetic activity for the ensuing cycle 25 is important in space weather service for planning future space missions. This study analyzed the **highest (aa_{H}) and lowest aa index (aa_{L}) from 24 three-hourly values in 3-day-interval, smoothed by 363 days (121 points) to mimic the 13-month smoothing. It is found that the maximum (aa_{Hmax}) of aa_{H} is well correlated to both the preceding minimum (aa_{Hmin},$r = 0.85$) of aa_{H} and the preceding minimum (aa_{Lmin},$r = 0.89$) of aa_{L} for the 11-year solar cycle. Based on these relationships the strength of geomagnetic activity for the ensuing cycle is predicted to be $aa_{\mathsf{Hmax}}(25) = 85.5 \pm 6.9$ (nT), about 32% stronger than that of cycle 24. This value is equivalent to the Ap index of $Ap_{\mathsf{max}}(25) = 56.0 \pm 4.8 \pm 1.2$ (nT). The maximum (aa_{Lmax}) of aa_{L} is also found to be well correlated to the preceding $aa_{\mathsf{Hmin}}(r = 0.80)$. The solar activity is much better correlated to the strong geomagnetic activity (aa_{Hmax},$r = 0.79$) than to the weak one (aa_{Lmax},$r = 0.37$).** The rise time of aa_{Hmax} (T_{Hr}) is found to be weakly anti-correlated to the following maximum (aa_{Hmax}), $r = -0.42$ at the 84% confidence level. **Using this correlation and the predicted $aa_{\mathsf{Hmax}}(25)$, one can roughly estimate the rise time, $T_{\mathsf{Hr}}(25) = 5.2 \pm 2.0$ (years)**, implying that the geomagnetic activity for the ensuing cycle 25 would peak around August 2025± 2.0 (years).

1 Introduction

Studying and predicting geomagnetic activities are important in both geophysics and space weather. Severe geomagnetic activities may cause intense geomagnetic storms (Gonzalez et al., 1989, 1994; Chen et al., 2019), leading to disruptions in communication and deviations of spacecrafts. With the current solar cycle 24 approaching its end, satellite and spacecraft-related departments want to know the strengths of both solar and geomagnetic activities in the ensuing cycle 25 for planning future space missions.

Among various indices to quantitatively describe the geomagnetic activity, the aa index (Mayaud, 1972), derived from the 3-hourly K indices at two near-antipodal midlatitude stations in England and Australia, is the longest time series (since 1868) and has been widely used for analyzing long-term trends in the global geomagnetic activity (Russell and Mulligan, 1995; Marat et al., 2017; Du, 2011a; El-Borie et al., 2019) and for analyzing its correlation with both climate change (Cliver et al., 1998; Dobrica et al., 2009; Gavrilyeva et al., 2017) and solar activity (Echer et al., 2004; Prestes et al., 2006; Lukianova et al., 2009; Du, 2011b,c; Du and Wang, 2012; Singh and et al., 2019). The minimum aa index (aa_{min}), at or near the minimum of the solar cycle, has been widely used in predicting the maximum amplitude of the sunspot cycle (R_{m}), the so-called Ohl's precursor method (Ohl, 1979; Brown and Williams, 1969; Du et al., 2009). But it is seldom used to directly predict the maximum aa index (aa_{max}) of an ensuing cycle.

The planetary geomagnetic index Ap (Bartels, 1963) available since 1932, derived from the average of the measurements at 13 observatories around the globe, is a daily measure of the response of geomagnetic field to variations in the interplanetary magnetic field (IMF) and the solar wind (Li, 1997; McPherron, 1999; Tsurutani et al., 2006). It is the main global magnetic index forecasted by government agencies (McPherron, 1999). Most works on forecasting geomagnetic activity have been over short intervals, on the order of hours or days (McPherron, 1999; Abunina et al., 2013). In the earlier years, Kane (1988) pointed out that it is impossible to forecast the long-term geomagnetic activity through analyzing the daily, monthly and annual values of Ap and aa indices. Gordon (2015) demonstrated that long-term geomagnetic activity can only be predicted to within a limited threshold of accuracy due to the irregular trends and cycles in the annual data and nonlinear variability in the monthly series, through analyzing the aa index.

In this study, we analyze the **highest (aa_{H}) and lowest (aa_{L}) 3-hourly aa index in each 3 days' interval, smoothed by 363 days (121 points) to mimic the 13-month smoothing. It is found that the maximum (aa_{Hmax}) of aa_{H} is well correlated to both the preceding minimum (aa_{Hmin}) of aa_{H} and the preceding minimum (aa_{Lmin}) of aa_{L} for the 11-year solar cycle, which can be used to predict aa_{Hmax}.**

This study is arranged as follows. The data used in the current work are shown in Sect. 2. Section 3 is devoted for the results. First, in Sect. 3.1, we **analyze** the relationships between the maximum **of the smoothed highest 3-hourly aa index (aa_{Hmax}) in 3 days and the preceding minima of both the smoothed highest (aa_{Hmin}) and lowest (aa_{Lmin}) 3-hourly aa indices in 3 days, followed by a prediction of** aa_{Hmax} for cycle 25. **The relationship between the maximum of aa_{L} (aa_{Lmax}) and the preceding aa_{Hmin} is simply analyzed in Sect. 3.2.** In Sect. 3.3, we analyze the relationship between the rise time of aa_{H} from aa_{Hmin} to aa_{Hmax} and the following maximum for the 11-year cycle, so as to estimate the peak time of geomagnetic activity for the ensuing cycle. Some conclusions are discussed and summarized in Sect. 4.

2 Data

In this study, we use the **3-hourly** aa index since 1868 from the International Service of Geomagnetic Indices (ISGI)[1]. **For each 3-day-interval, we find the highest aa index (aa_{H}) and the lowest aa index (aa_{L}) from 24 values of the 3-hourly aa indices. Then, both aa_{H} and aa_{L} are smoothed by 363 days (121 points) to mimic the 13-month smoothing, as shown in Fig. 1 (solid). The (13-month) smoothed monthly mean International sunspot number series (R_{I}, Clette et al., 2016) of the second version[2] is used for comparison (dotted).**

The parameters used in this study are listed in Table 1, in which aa_{Hmin} (aa_{Hmax}) is the minimum (maximum) of aa_{H}, aa_{Lmin} (aa_{Lmax}) the minimum (maximum) of aa_{L}, T_{Hr} the rise time of aa_{H} from aa_{Hmin} to aa_{Hmax}, and R_{m} the maximum of R_{I} for the 11-year solar cycle. The last row denotes the averages of the parameters.

[1]http://isgi.unistra.fr/
[2]http://www.sidc.be/silso/datafiles

Table 1. The minimum (aa_{Hmin}) and maximum (aa_{Hmax}) of the 363-day smoothed highest 3-hourly aa index (aa_{H}) in each 3 days, the rise time of aa_{Hmax} (T_{Hr}), the minimum (aa_{Lmin}) and maximum (aa_{Lmax}) of the 363-day smoothed lowest 3-hourly aa index (aa_{L}) in each 3 days, and the maximum (R_{m}) of 13-month smoothed sunspot number for solar cycles 11-25.

n	aa_{Hmin}(nT)	aa_{Hmax}(nT)	T_{Hr}(yr)	aa_{Lmin}(nT)	aa_{Lmax}(nT)	R_{m}
11		88.24			4.29	234.0
12	21.41	79.60	3.81	2.00	4.60	124.4
13	31.88	86.92	2.08	2.58	4.47	146.5
14	19.40	59.55	8.47	2.00	4.37	107.1
15	25.31	73.28	5.72	2.19	5.80	175.7
16	30.80	75.90	5.56	2.07	7.56	130.2
17	41.60	84.01	4.01	2.52	6.36	198.6
18	51.13	88.31	6.57	3.02	7.18	218.7
19	49.60	100.99	5.89	3.08	7.66	285.0
20	43.08	79.31	7.54	2.55	8.79	156.6
21	49.35	97.87	2.63	3.52	7.96	232.9
22	48.93	103.89	4.78	3.57	9.73	212.5
23	47.84	99.75	5.92	2.98	10.22	180.3
24	25.02	64.81	5.73	2.17	5.27	116.4
25	33.24			2.94		
Av.	37.04	84.46	5.29	2.66	6.73	179.9

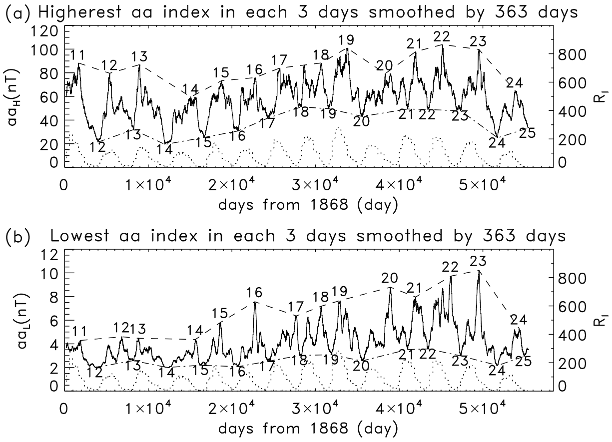

Fig. 1. (a) The highest aa index (aa_{H}) and (b) the lowest aa index (aa_{L}) in each 3 days, smoothed by 363 days. The numbers in the figure indicate the 11-year solar cycles. The upper dashed and lower dash-dotted lines indicate the maxima and minima, respectively, for the 11-year cycle. The dotted line represents the smoothed monthly mean sunspot number (R_{I}) for comparison.

3 Result

The correlation coefficients between the parameters in Table 1 are listed in Table 2 for comparison. It is seen in Table 2 that R_{m} is well correlated to $aa_{\mathrm{Hmin}}(r = 0.84)$, $aa_{\mathrm{Hmax}}(r = 0.79)$, $aa_{\mathrm{Lmin}}(r = 0.81)$, and positive correlated to $aa_{\mathrm{Lmax}}(r = 0.37)$. It implies that the stronger the solar activity (R_{I}), the higher the geomagnetic activity (aa). But the solar activity is much better correlated to the strong geomagnetic activity (aa_{Hmax}) than to the weak one (aa_{Lmax}), the latter may be due to the high speed solar wind streams which is out of phase with the solar activity cycle (Feynman, 1982; Hathaway and Wilson, 2006). The

Table 2. The correlation coefficient (r) between parameters x and y.

x/ y	aa_{Hmin}	aa_{Hmax}	T_{Hr}	aa_{Lmin}	aa_{Lmax}	R_{m}
aa_{Hmin}	1.00	0.85	−0.10	0.87	0.80	0.84
aa_{Hmax}	0.85	1.00	−0.42	0.89	0.63	0.79
T_{Hr}	−0.10	−0.42	1.00	−0.28	0.13	−0.18
aa_{Lmin}	0.87	0.89	−0.28	1.00	0.70	0.81
aa_{Lmax}	0.80	0.63	0.13	0.70	1.00	0.37

correlation between R_{m} and aa_{Hmin} (or aa_{Lmin}) is related to the Ohl's precursor method (Ohl, 1979) for predicting R_{m}. Other significant correlations can be used to predict aa_{Hmax} (Sect. 3.1), aa_{Lmax} (Sect. 3.2), and T_{Hr} (Sect. 3.3) in this study.

3.1 Relationship between the maximum and preceding minimum

It is seen in Table 2 that aa_{Hmax} is well correlated to the preceding $aa_{\mathsf{Hmin}}(r=0.85)$ and $aa_{\mathsf{Lmin}}(r=0.89)$, as shown in Fig. 2 for the scatter plots of aa_{Hmax} against aa_{Hmin}(a) and aa_{Lmin}(b). The solid line represents a linear fit of aa_{Hmax} to aa_{Hmin} (aa_{Lmin}) with the least-squares-fit regression equations given by

$$\begin{cases} aa_{\mathsf{Hmax}} = 47.1 \pm 7.1 + (0.99 \pm 0.18) aa_{\mathsf{Hmin}}, \ \sigma = 7.3, \\ aa_{\mathsf{Hmax}} = 25.3 \pm 9.4 + (22.3 \pm \ \ 3.5) aa_{\mathsf{Lmin}}, \ \sigma = 6.5, \end{cases} \tag{1}$$

where $\pm$ represents the 1σ deviation and σ the standard deviation of the fitting.

Therefore, the aa index at the minimum can be used as an indicator to predict the index at the maximum. From the above relationships, one can predict aa_{Hmax} for cycle $n=25$ by substituting the values of aa_{Hmin}(33.24 nT) and aa_{Lmin}(2.94 nT) into these equations,

$$\begin{cases} aa_{\mathsf{Hmax1}}(25) = 80.1 \pm 7.3(\mathsf{nT}), \text{ from } aa_{\mathsf{Hmin}}, \\ aa_{\mathsf{Hmax2}}(25) = 91.0 \pm 6.5(\mathsf{nT}), \text{ from } aa_{\mathsf{Lmin}}, \end{cases} \tag{2}$$

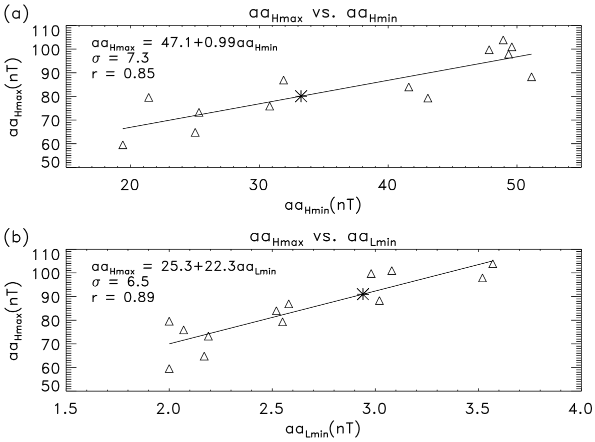

Fig. 2. (a) Scatter plot of $aa_{\rm Hmax}$ against $aa_{\rm Hmin}$ (triangles) and the linear fit (solid). (b) Scatter plot of $aa_{\rm Hmax}$ against $aa_{\rm Lmin}$(triangles) and the linear fit (solid).

(labelled by asterisk). As the above relationships have a similar correlation (0.85 and 0.89), we take the prediction of $aa_{\rm Hmax}(25)$ as the average,

$$\begin{aligned} aa_{\rm Hmax}(25) &= \frac{1}{2}[aa_{\rm Hmax1}(25) + aa_{\rm Hmax2}(25)] \\ &= 85.5 \pm 6.9({\rm nT}). \end{aligned} \quad (3)$$

It implies that the 363-day smoothed highest 3-hourly aa index in 3-day-interval during the maximum period of cycle 25 is predicted to be close to the average (84.46 nT) over the past cycles (Table 1), but higher than that (64.81 nT) of cycle 24 by about 32.0%.

It should be pointed out that the above prediction may be an upper estimate for the maximum aa index as cycle 24 has not completely passed. Although we are not quite sure if the current $aa_{\rm H}$ ($aa_{\rm L}$), 33.94 (3.47) in November 2019, would decrease to a smaller value than that, 33.24 (2.94), used in the current work, there would not be significant variations

in aa_{Hmin}, aa_{Lmiin} and the above prediction, as the solar (sunspot) activity (R_{I}) shows a sign to stop decreasing and to oscillate around the minimum in the recent few months.

3.2 Relationship between aa_{Lmax} and the preceding aa_{Hmin}

It is seen in Table 2 that aa_{Lmax} is also well correlated to the preceding $aa_{\mathsf{Hmin}}(r = 0.80)$, as shown in Fig. 3(a) for the scatter plot of aa_{Lmax} against aa_{Hmin}. The linear fitting equation of aa_{Lmax} to aa_{Hmin} (solid) is

$$aa_{\mathsf{Lmax}} = 2.0 \pm 1.2 + (0.131 \pm 0.030) aa_{\mathsf{Hmin}}, \ \sigma = 1.2. \tag{4}$$

Substituting $aa_{\mathsf{Hmin}}(25) = 33.24$ (nT) into this equation, one can estimate the 363-day smoothed lowest 3-hourly aa index in 3-day-interval during the maximum period of cycle 25, $aa_{\mathsf{Lmax}} = 6.4 \pm 1.2$ (nT). This value is close to the average (6.73 nT) over the past cycles, but higher than that (5.27 nT) of cycle 24 by 21.1%.

3.3 Relationship between the rise time and maximum

At last, in this section, we analyze if the rise time of the geomagnetic index for the 11-year cycle **is correlated to** the following maximum **so that it can be used to estimate the rise time**, as the case in sunspot cycle (Waldmeier, 1939).

Figure 3(b) shows the scatter plot of the rise time (T_{Hr}) from aa_{Hmin} to aa_{Hmax} for the 11-year cycle against **its following** maximum (aa_{Hmax}). It is seen in this figure that T_{Hr} **is weakly anti-correlated to aa_{Hmax}, with a correlation coefficient of $r = -0.42$ at a confidence level of about 84%. The linear fitting equation of T_{Hr} to aa_{Hmax} is**

$$T_{\mathsf{Hr}} = 9.9 \pm 3.0 - (0.055 \pm 0.036) aa_{\mathsf{Hmax}}, \ \sigma = 1.6. \tag{5}$$

Using this weak correlation, one can roughly estimate the rise time, $T_{\mathsf{Hr}}(25) = 5.2 \pm 0.4 \pm 1.6$ (years), by substituting the predicted value of $aa_{\mathsf{Hmax}}(25) = 85.5 \pm 6.9$ (nT) in Eq. (3) into this equation, here ± 0.4 is derived from the uncertainty (± 6.9) of $aa_{\mathsf{Hmax}}(25)$. Certainly, this estimate is less reliable than the prediction on the maximum.

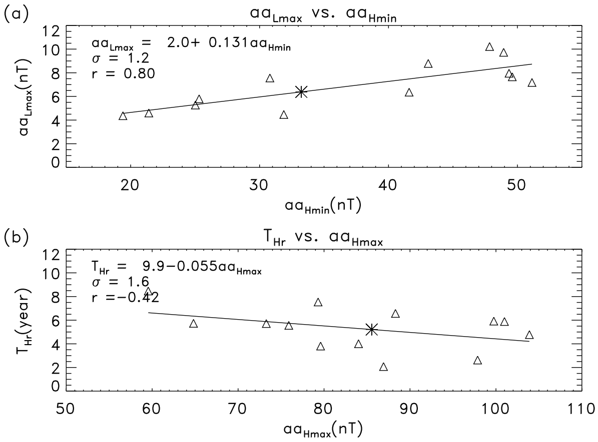

Fig. 3. (a) Scatter plot of aa_{Lmax} against aa_{Hmin} (triangles) and the linear fit (solid). (b) Scatter plot of T_{Hr} against aa_{Hmax} (triangles) and the linear fit (solid).

At the current state, the smoothed monthly mean sunspot number is as low as 3.1 in September 2019. The monthly mean values for the last few months appear in an oscillation around the minimum. So the minimum time of cycle 25 should not be far from September 2019 ($\pm$ 8 months, Du and Wang, 2011). If the minimum time of aa index is (temporarily) taken as that of sunspot activity with an average delay of 9 months (Legrand and Simon, 1981; Wang and Sheeley, 2009; Du, 2011b), then the peak time of $aa_{\mathsf{Hmax}}(25)$ would be roughly estimated to be around September 2019 $+9$ (months) $+T_{\mathsf{Hr}}(25) \sim$ August 2025± 2.0 (years).

4 Discussions and Conclusions

It is well known that the aa index is positively correlated to the solar activity (R_I). In general, the stronger the solar activity, the higher the (aa) geomagnetic activity. But the correlation between aa and R_I is not very strong (Du, 2011b,c). We can only roughly evaluate the strength of geomagnetic activity from the strength of solar (sunspot) activity. In addition, the future solar activity is also unknown at the present time. The relationship between aa and R_I is not a simple linear one (Borello-Filisetti et al., 1992; Mussino et al., 1994; Kishcha et al., 1999; Lockwood et al., 1999; Echer et al., 2004). The aa index tends to lag behind R_I about 2–3 years around a solar cycle maximum (Wang et al., 2000; Echer et al., 2004), and (only) about 1 year around a cycle minimum (Legrand and Simon, 1981; Wang and Sheeley, 2009; Du, 2011b). The complicate relationship between aa and R_I can be better understood by an integral response model (Du, 2011c) that increases the correlation from 0.61 to 0.85.

There are many methods that can be used to predict the maximum amplitude of sunspot cycle (R_m), such as 1) statistical methods, employing the relationship between the inter-cycle parameters (Thompson, 1988; Hathaway et al., 1994) or the early rising rate (Thompson, 1988; Cameron and Schüssler, 2008; Du and Wang, 2012); 2) the functional methods, using mathematical functions of a few parameters (Hathaway et al., 1994; Du, 2011d) for extrapolating the following monthly values; 3) the geomagnetic precursor methods (Ohl, 1979; Brown and Williams, 1969; Du et al., 2009), using the geomagnetic activity near the solar minimum; and 4) the solar precursor ones (Schatten et al., 1978; Pesnell and Schatten, 2018), using the previous cycle's polar field.

In contrast, there are less methods found to predict the maximum amplitude of geomagnetic index. Geomagnetic activity forecast has been over the order of hours or days (McPherron, 1999; Abunina et al., 2013). The annual or monthly prediction on the geomagnetic activity is within a limited accuracy (over 20%) due to the irregular variation in the time series (McPherron, 1999; Gordon, 2015). In the earlier years, Kane

(1988) even pointed out that it is impossible to forecast the long-term geomagnetic activity through analyzing the time series of the Ap and aa indices (refer also to Gordon, 2015). The geomagnetic activity near the solar minimum or at the decreasing phase of the solar cycle has been widely used to predict the maximum amplitude of sunspot cycle, but were seldom used to predict the maximum amplitude of the geomagnetic activity itself.

In the current work, we analyzed the **highest (aa_{H}) and the lowest (aa_{L}) 3-hourly aa index in each 3-day-interval, smoothed by 363 days (121 points) to mimic the 13 months smoothing. It is found that the maximum (aa_{Hmax}) of aa_{H} is well correlated to both the preceding minimum ($aa_{\mathsf{Hmin}}, r = 0.85$) of aa_{H} and the preceding minimum ($aa_{\mathsf{Lmin}}, r = 0.89$) of aa_{L} for the 11-year solar cycle.** So, these relationships can be used to predict the strength of geomagnetic activity for the ensuing cycle, $aa_{\mathsf{Hmax}}(25) = 80.1 \pm 7.3$ (nT) or 91.0 ± 6.5 (nT), with an average of $aa_{\mathsf{Hmax}}(25) = 85.5 \pm 6.9$ (nT). It implies that the strength of **geomagnetic activity for** the ensuing cycle 25 would be similar to the average over the past cycles, but higher than that of cycle 24 **by about 32%. Certainly, this value is an upper estimate, as cycle 24 has not completely passed and we should check if there is an even smaller value of $aa_{\mathsf{Hmin}}(25)$ or $aa_{\mathsf{Lmin}}(25)$ than that used in the current work (33.24 or 2.94) in the future few months.**

If using the high correlation between the smoothed monthly mean Ap[3] and aa indices since 1932, $r = 0.94$, and the linear fitting equation of Ap to aa,

$$Ap = -1.35 \pm 0.17 + (0.694 \pm 0.008) aa, \sigma = 1.2, \tag{6}$$

the above prediction will be equivalent to $Ap_{\mathsf{max}}(25) = 56.0 \pm 4.8 \pm 1.2$ (nT), here ± 4.8 is derived from the uncertainty (± 6.9) of $aa_{\mathsf{Hmax}}(25)$.

The well known 'Waldmeier effect' (Waldmeier, 1939) that the rise time of a solar cycle is well anti-correlated to the amplitude has been widely used to estimate the rise and peak times of a solar cycle if the amplitude has been predicted. However, such a correlation **is very weak** in the aa geomagnetic index. The rise time of $aa_{\mathsf{Hmax}}(T_{\mathsf{Hr}})$

[3] http://www.gfz-potsdam.de/en/kp-index

for the 11-year cycle is found to be weakly anti-correlated to the following maximum (aa_{Hmax}), $r = -0.42$ **at the 84% confidence level.** Using this correlation, one could roughly estimate the rise time, $T_{\mathsf{Hr}}(25) = 5.2 \pm 2.0$ (years), and the peak time, August 2025± 2.0 (years), of geomagnetic activity for the ensuing cycle 25. Certainly, this estimate is much less reliable than the predictions on the maximum.

According the analysis above, the following conclusions may be summarized,

1. **The maximum (aa_{Hmax}) of the 363-day smoothed highest 3-hourly aa index in 3-day-interval (aa_{H}) is found to be well correlated to both the preceding minimum (aa_{Hmin},$r = 0.85$) of aa_{H} and the preceding minimum (aa_{Lmin},$r = 0.89$) of the 363-day smoothed lowest 3-hourly aa index in 3-day-interval (aa_{L}) for the 11-year solar cycle.** As a result, the maximum for the ensuing cycle 25 is predicted to be $aa_{\mathsf{Hmax}}(25) = 85.5 \pm 6.9$ (nT), about 32% higher than that of cycle 24. **This value is equivalent to the Ap index of $Ap_{\mathsf{max}}(25) = 56.0 \pm 4.8 \pm 1.2$ (nT).**

2. **The maximum (aa_{Lmax}) of aa_{L} is also found to be well correlated to the preceding aa_{Hmin}, $r = 0.80$. Based this correlation, $aa_{\mathsf{Lmax}}(25)$ is predicted to be 6.4 ± 1.2 (nT).**

3. **The solar activity is much better correlated to the strong geomagnetic activity (aa_{Hmax}, $r = 0.79$) than to the weak one (aa_{Lmax},$r = 0.37$).**

4. **The rise time (T_{Hr}) is found to be weakly correlated to the following maximum (aa_{Hmax}) for the 11-year cycle, $r = -0.42$ at the 84% confidence level.** Using this correlation, one could roughly estimate the rise time, $T_{\mathsf{Hr}}(25) = 5.2 \pm 2.0$ (years), and the peak time, August 2025± 2.0 (years), of geomagnetic activity for the ensuing cycle 25.

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