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Solar cycles during the seventeenth century revealed by equatorial aurora records

Yong Wei[1,2], and LiMei Yan[1,2*]

[1]Key Laboratory of Earth and Planetary Physics, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China;

[2]College of Earth and Planetary Sciences, University of Chinese Academy of Sciences, Beijing 100049, China

Key Points:

- Utilizing historical records of red equatorial aurorae, the minima and maxima years of solar cycles between 1623 and 1700 are determined and evaluated.
- Contrary to the previously accepted count of 12 solar cycles, a thorough analysis reveals 13 solar cycles taking place between 1610 and 1755.
- The red equatorial aurorae recorded in ancient Korean historical texts serve as a valuable data source for studying solar activity.

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Abstract: Solar cycles are fundamental to astrophysics, space exploration, technological infrastructure, and Earth's climate. A better understanding of these cycles and their history can aid in risk mitigation on Earth, while also deepening our knowledge of stellar physics and solar system dynamics. Determining the solar cycles between 1600 and 1700 — especially the post-1645 Maunder Minimum, characterized by significantly reduced solar activity — poses challenges to existing solar activity proxies. This study utilizes a new red equatorial auroral catalog from ancient Korean texts to establish solar cycle patterns from 1623 to 1700. Remarkably, a further reevaluation of the solar cycles between 1610 and 1755 identified a total of 13 cycles, diverging from the widely accepted record of 12 cycles during that time. This research enhances our understanding of historical solar activity, and underscores the importance of integrating diverse historical sources into modern analyses.

Keywords: solar cycle; Maunder Minimum; solar activity; red equatorial aurora; West Pacific geomagnetic anomaly

1. Introduction

Understanding the rising and falling of solar activity, as manifested in solar cycles, is a cornerstone of astrophysical studies with profound implications across a multitude of scientific disciplines. Solar activity has a profound impact on Earth and human activities, including modulating the planetary climate, and causing the orbital decay of man-made satellites. Over a span of approximately 11 years, the sun undergoes a cycle characterized by fluctuations in the emission of solar radiation, as well as the number of sunspots, solar flares, and coronal mass ejections (Usoskin, 2017). These cycles are not merely curiosities of our star’s behavior; they are pivotal factors in defining the heliospheric environment.

The historical journey to understanding the solar cycle began in the 1770s, with Christian Horrebow's initial hypothesis about the cyclical recurrence of sunspots (Hathaway, 2015). The hypothesis was rediscovered by Heinrich Schwabe in 1844 (Schwabe and Herrn, 1844), who observed a decadal pattern in the fluctuating number of sunspots on the Sun's surface. This inspired Rudolf Wolf at the Zurich Observatory to undertake a comprehensive collection of historical sunspot records, leading to the first calculation of the Wolf sunspot number (WSN) series in 1848. The WSN metric combines the count of individual sunspots and groups, weighted to reflect their significance (Wolf, 1861). This paradigm shifted in 1998, when Douglas Hoyt and Kenneth Schatten (Hoyt and Schatten, 1998) undertook a meticulous review of all extant historical records and established an alternative metric, the group sunspot number (GSN), providing a fresh perspective on long-term solar activity.

The quest to map the solar cycles over the past 400 years, particularly preceding the first solar cycle (1755–1766), remains an ongoing and contentious scholarly endeavor. Despite the development of both the WSN and the GSN, a consensus on the solar activity throughout these early periods has remained elusive. The primary obstacle in this historical reconstruction is the significant dearth of reliable observational data from the 1600s and 1700s (Muñoz-Jaramillo and Vaquero, 2019). The Maunder Minimum, a prolonged interval of reduced sunspot activity from approximately 1645 to 1715, epitomizes the challenges faced by researchers. This period predates systematic sunspot recording, and the scant observations that do exist on record are fragmentary and often

First author: Y. Wei, weiy@mail.iggcas.ac.cn
Correspondence to: L. M. Yan, lmyan@mail.iggcas.ac.cn
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contradictory. Consequently, scientists are compelled to employ indirect methods, such as analyzing cosmogenic isotopes like the carbon-14 or beryllium-10 found in tree rings and ice cores (e.g., Beer et al., 1998; Miyahara et al., 2004; Poluianov et al., 2014), which are used to infer historical solar activity.

Another approach to discerning past solar cycles is to employ the indirect solar indices reserved in historical archives, rather than those in the natural record Chronicles of astronomical phenomena contained within these archives, such as observations of the coronal structure during solar eclipses (e.g., Hayakawa et al., 2021), sunspots (e.g., Xu ZT and Jiang YT, 1982; Ribes and Nesme-Ribes, 1993; Nagovitsyn, 2007; Vaquero et al., 2015), and aurorae (e.g., Schlamminger, 1990; Schröder, 1992; Silverman, 1992), offer substantial evidence to piece together the solar activity puzzle. We compiled a new auroral catalog from ancient Korean historical books of the Koryo-Sa, the Choson Wangjo Sillok, and the Seungjeongwon Ilgi. Using automatic retrieval from the digital books, with formatted keywords and manual confirmation for each record (Wei Y and Wan WX, 2020; Wang YQ et al., 2021), we found clear evidence of an eight-year solar cycle during the Maunder Minimum (Yan LM et al., 2023), rather than the commonly described 11-year cycle for the same period. We use this catalog to extract further details about solar cycles during the seventeenth century.

2. Data and Methods

On Earth, a dynamic and distinct red equatorial aurora can occur in the region of the low-intensity geomagnetic field anomaly, such as the South Atlantic Anomaly (SAA). The rare phenomenon is caused by high energy particles penetrating deep into the atmosphere during geomagnetic storms (He F et al., 2021). Thus the red equatorial aurora is closely related to solar activity. From 1500 to 1800 AD, across the Maunder Minimum, a low-intensity geomagnetic anomaly was recorded in the West Pacific region (He F et al., 2021), named the West Pacific Anomaly (WPA). During the same period, numerous red aurorae were recorded in ancient Korean historical books, which were recently compiled into a new catalog of aurorae (Wei Y and Wan WX, 2020; Wang YQ et al., 2021). In our research, we primarily use the red equatorial aurorae observed in the southern nocturnal sky (south, southwest, and southeast) of the Korean Peninsula, which is attributed to energetic particle precipitation in the WPA (He F et al., 2021), and provides a new source of data for historical solar activity. Notably, during the Maunder Minimum, the red equatorial aurorae were particularly prominent, commonly linked to the evolution of the paleo-West Pacific geomagnetic anomaly (He F et al., 2021).

Using this new data about the occurrence of the red equatorial aurora, we estimate the minima and maxima years of each solar cycle. Based on our findings, after 1700, aurora occurrence decreased significantly with the increase in geomagnetic intensity in the WPA (He F et al., 2021). For the period from 1623 to 1700, the annual records of red equatorial aurorae serve as a proxy for solar activity to determine cycle minima and maxima (Figure 1a). For the period before 1623 and after 1700, we adopted cycle dates previously derived from the sunspot number (Waldmeier,

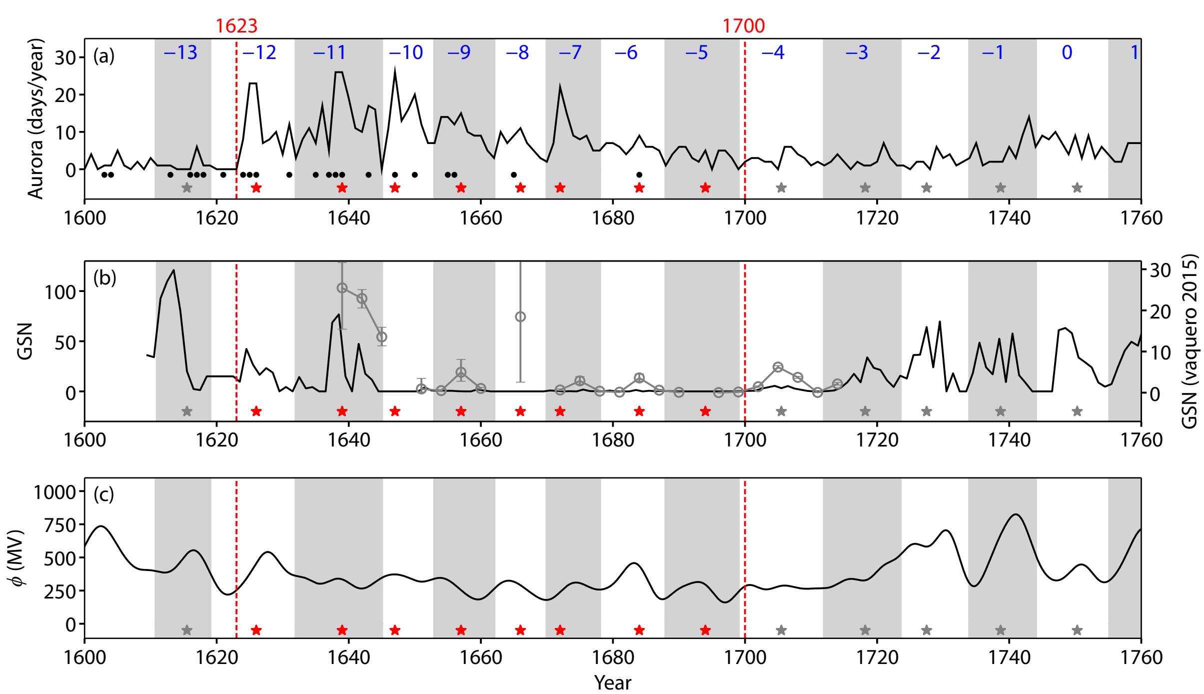

Figure 1. Comparison of the red equatorial aurora and other proxies of solar activity. (a) the occurrence of red equatorial aurora (dark red bars) alongside the years when naked-eye sunspots were documented (dark dots) in Chinese local gazettes. (b) the original version 1 GSN (dark line) and the GSN deduced from active-day fractions (grey line). (c) the black line shows the solar modulation parameter ϕ provided by Brehm N et al. (2021). Grey shadows across all panels indicate the span of solar cycles starting from the minima. Red stars pinpoint cycle maxima determined from red equatorial aurora, whereas grey stars mark cycle maxima based on sunspot cycle data from NOAA/NCEI. The grey and white boxes label the solar cycles. The junction between grey box and white box label the cycle minimum.

1961), which are publicly available on NOAA.

To evaluate the reliability of the solar cycle minima and maxima determined from Korean equatorial aurora records, we utilized three key sunspot datasets: the version 1 group sunspot number (GSN) provided by Hoyt and Schatten (1998); the GSN derived from the active-day fractions by Vaquero et al. (2015); and the Chinese naked-eye sunspots in local gazetteer collected by Xu ZT and Jiang YT (1982). The proportion of the rise time relative to the total solar cycle length is further utilized to conduct the evaluation. The solar modulation parameter ϕ (in MV) reconstructed from radionuclide records (Brehm et al., 2021) is used to compare records of red equatorial aurorae.

3. Results

3.1 The Identified Cycle Maxima and Minima

Between 1623 and 1645, the year with the fewest auroral events is estimated to be 1632. Yan LM et al. (2023) pinpointed the cycle lows between 1645 and 1678, as marked by equatorial aurorae, as occurring in 1645, 1653, 1662, 1670, and 1678. For the period 1678 to 1700, the years 1688 and 1699 are estimated as the cycle minima. Using the identified cycle minima, we established the sequence of solar cycles prior to 1755, as outlined in Table 1. While earlier research typically identifies 12 solar cycles between 1610 and 1755 (e.g., Waldmeier, 1961; Link, 1978; Beer et al., 1998; Nagovitsyn, 2007; Velasco Herrera et al., 2022), the distinctive clarity of equatorial auroras during the Maunder Minimum has allowed for a more precise determination of solar cycles within that period (see Table S1 in Supplementary Material). Consequently, the revised count is 13 cycles instead of 12 for the timeframe from 1610 to 1755.

With the established cycle minima, the maximum year for the cycles between 1623 and 1700 is determined as the year with maximum auroral records for each solar cycle. From cycle −12 to −6, the years with maximum auroral records are estimated to be 1626, 1639, 1647, 1657, 1666, 1672, and 1684. For cycle −5 from 1688 to 1699, the maximum year is estimated to be 1694, which corresponds to the second peak in aurora occurrence.

3.2 The Evaluation of the Cycle Maxima and Minima by the Sunspot Datasets

Prior to the Maunder Minimum, between the years 1623 and 1645, the clustering of Chinese records of naked-eye sightings of sunspot around the times of the red aurora and GSN peaks (1626 and 1639, respectively) indicates a strong correlation (Figures 1a and 1b). These Chinese records provide valuable confirmation of cycle maxima identified during the Maunder Minimum.

The six solar cycles between 1645 and 1700, as defined by consecutive minima, have been evaluated by the sunspot datasets. These cycles, identified through equatorial aurorae (Figure 1a), show alignment with the GSN calculated from active-day fractions (grey lines in Figure 1b). Specifically, cycles −9, −7, and −6 correlate closely with the GSN from active-day fractions. This strong consistency underscores the reliability of cycle minima determined for the years 1653, 1662, 1670, 1678, and 1688. Furthermore, the

Table 1. The solar cycle parameters from 1610 to 1755.

Cycle number	T_{min}	T_{max}	Length	T_{rise}	T_{rise}/Length
−13	1610.8*?	1615.5*?	8.2?	4.7	0.57
−12	1619*?	1626	13?	7	0.54
−11	1632?	1639	13	7	0.54
−10	1645	1647	8	2	0.25
−9	1653	1657	9	4	0.44
−8	1662	1666	8	4	0.5
−7	1670	1672?	8	2	0.25
−6	1678	1684	10	6	0.6
−5	1688	1694?	11	6	0.55
−4	1699	1705.5*	13	6.5	0.5
−3	1712*	1718.2*	11.5	6.2	0.54
−2	1723.5*	1727.5*	10.5	4	0.38
−1	1734*	1738.7*	11	4.7	0.43
0	1745*	1750.3*	10.2	5.3	0.52
1	1755.2*	1761.5*			

Note: T_{min} and T_{max} shows the minimum years and the maximum years of each solar cycle. The cycle minima and maxima between 1623 and 1700 are identified from the red equatorial aurora. The solar cycle length is obtained from the two successive solar minima. T_{rise} shows the rise time from the minimum to the maximum for each solar cycle. T_{rise}/Length show the ratio of the rise time and the cycle length (T_{rise}/Length). *The cycle minimum or maximum derived from the monthly mean sunspot number (Waldmeier, 1961). ?The minimum/maximum needs further evaluation in the future.

cycle minima of 1645 and 1699 are deemed reliable when compared to both version 1 of the GSN, and the GSN based on active-day fractions. The patterns of the red equatorial aurorae were also compared with the solar modulation parameter ϕ (Figure 1c), showing some degree of consistency (Figures 1a and 1c).

The maxima of solar cycles determined from the red equatorial aurorae during the Maunder Minimum have been primarily assessed using the GSN, based on active-day fractions (grey lines in Figure 1b) and Chinese naked-eye sunspots (dark dots in Figure 1a). The peaks of cycles −9 and −6 coincide with the GSN peaks and the presence of Chinese naked-eye sunspots, lending credibility to the identified maxima for 1657 and 1684. Cycles −10 and −8 also correspond to years with Chinese naked-eye sunspots. However, there is a discrepancy for the maximum of cycle −7 in 1672, which does not align with the GSN peak in 1675. For the maximum of cycle −5 in 1694, there is a lack of data from both the Chinese naked-eye sunspots and the two GSN datasets to confirm its accuracy. The maxima for cycles −7 and −5 are thus marked as uncertain and require further investigation.

After 1700, the cycle maxima (marked as grey stars in Figure 1) derived from the sunspot observations show inconsistency with the peaks of the red equatorial aurora records. This is probably owing to the recovery of the low-intensity geomagnetic anomaly WPA (He F et al., 2021), and consequently the rapid decrease of the red equatorial aurora occurrence.

3.3 Evaluation of the Cycle Maxima and Minima by the Rise Time Proportion

As previously reported, the documented solar cycles are asymmetric with respect to their maxima (Waldmeier, 1935). The rise time from minimum to maximum is usually shorter than the fall time from maximum down to the minimum (Hathaway, 2015). The rise time is also inversely proportional to the cycle amplitude, due to what is known as the Waldmeier Effect (Waldmeier, 1935, 1939).

The sunspot data for solar cycles 0 to 24 is relatively reliable and can help us identify consistent patterns. Using solar cycle parameters from NOAA/NCEI for cycles 0 to 24, we explored the relationship between rise time, its proportion relative to cycle length, and solar cycle intensity, to identify a threshold that distinguishes between strong and weak solar cycles. The lengths of cycles 0 to 24 is around 11 years (Figure 2c). Both the rise time and its proportion are strongly correlated with solar cycle intensity (Figures 2a, b, d).

Notably, we found that the average rise time proportion for cycles 0 to 24 is 0.4, which serves as a threshold for differentiating between strong and weak solar cycles. For cycles 0 to 24, when the annual sunspot number during the solar maximum exceeds 140 (noted above the orange dashed line in Figure 2a), the rise time proportion is less than or equal to 0.4, typically around 0.33. In contrast, when the peak sunspot number is below 140 (noted below the orange dashed line and shaded in gray in Figure 2), the

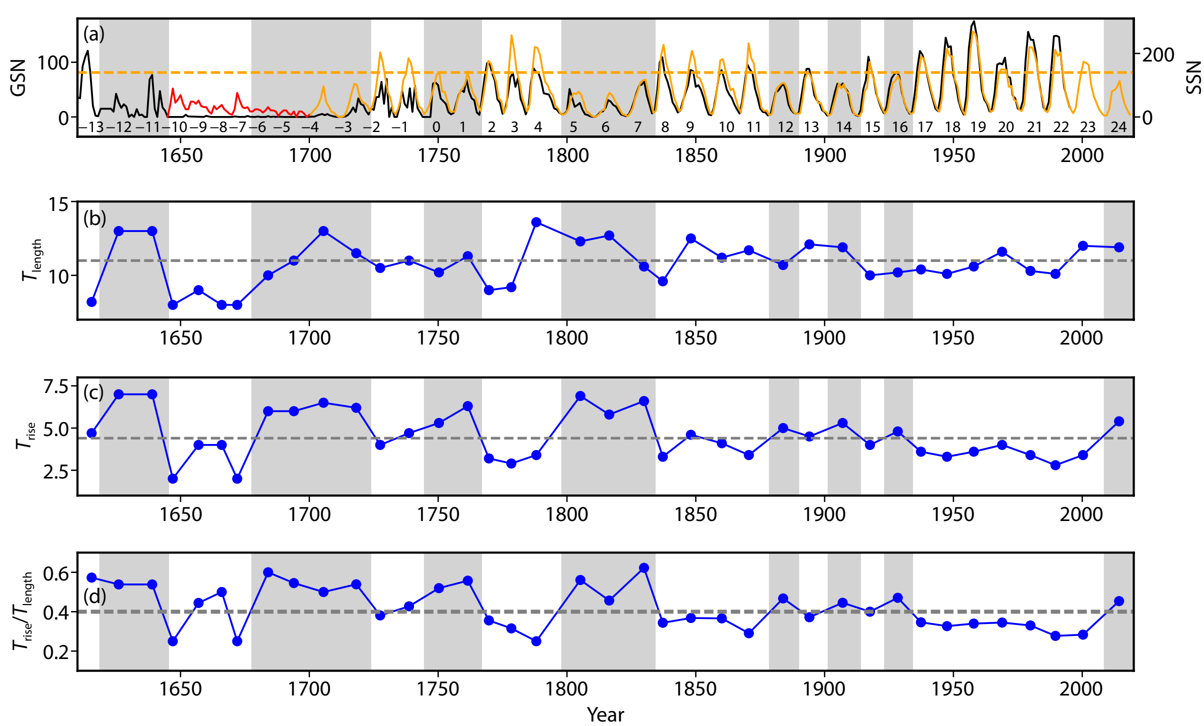

Figure 2. The solar activity proxies and the solar cycle parameters from cycle −13 to cycle 24. (a) Solar activity proxies, including yearly GSN (black line), SSN (orange line), and red equatorial aurora scaled by a factor of two (red line). The dashed orange line marks a yearly SSN value of 140. (b) Cycle lengths determined from the minima. The dashed grey line represents the mean cycle length (11 years) from Cycle 0 to Cycle 24. (c) Rise time for each solar cycle. The dashed grey line marks the average rise time (4.4 years) from Cycle 0 to Cycle 24. (d) Ratio of rise time to cycle length for each solar cycle. The dashed grey line indicates the mean ratio (0.4) from Cycle 0 to Cycle 24.

rise time proportion is greater than 0.4. Thus, the rise time proportion serves as an indicator of solar cycle strength, effectively distinguishing between strong and weak solar cycles. This method can also be applied to assess the weaker solar cycles during the Maunder Minimum.

There are four solar cycles from 1620 to 1700 (cycles −12, −11, −6, and −5), as determined by red equatorial aurora, following a roughly 11-year cycle . We found that these four cycles have a rise time proportion greater than 0.4, corresponding to weaker solar cycles. This finding supports the validity of the solar cycle information for cycles −12, −11, −6 and −5 obtained in this study. Interestingly, the four 8-year cycles determined by red equatorial aurorae also follow the same pattern, where the rise time proportion of 0.4 effectively distinguishes between relatively strong (−10 and −7) and weak (−9 and −8) solar cycles (Figures 2a and 2d).

4. Discussion and Conclusions

For years, researchers have pieced together an account of solar activity levels using historical records of aurorae. Using these methods, an extensive record of auroral occurrences below 55°N latitude from 1000 to 1900 CE has been constructed. However, these polar aurorae typically signal periods of intense solar activity, rather than the full range of solar cycle variations (Chen S et al., 2021). The red equatorial aurora records we examined in this research are particularly valuable for tracing solar cycle fluctuations. Their advantages are manifold: 1) They were meticulously recorded under royal mandate, ensuring high accuracy and consistency; 2) The records offer a long, uninterrupted chronology, spanning from 1623 to 1811 with daily logs; 3) They boast exceptional temporal and location detail, with observations taken every two hours and a spatial precision within 45-degree segments. These factors suggest that equatorial auroral records are comparable to modern scientific data in their reliability, surpassing the utility of polar aurora records for this purpose. It is worth noting that the fewer auroral records between 1610 and 1623 are due to incomplete documentation, and the evolution of the WPA (He F et al., 2021). During this period, the geomagnetic field intensity in the WPA is not low enough to produce many auroras.

Fortunately, the Maunder Minimum, a period of significant solar inactivity, coincided with a pronounced paleo-West Pacific Anomaly. This concurrence of events has provided a valuable basis for correlating and interpreting solar activity through equatorial aurora data collected during one of the most enigmatic periods in solar history. The data's accuracy and detail are significant enough to form an essential basis for understanding the intricacies of solar cycles since the advent of the telescope. By analyzing red equatorial auroras, we have established the minima and maxima years of solar cycles from 1623 to 1700, and reevaluated the sequence of solar cycles recorded before 1755. Our findings indicate that there were actually 13 solar cycles between 1610 and 1755, as opposed to the previously accepted 12. During the initial half of the Maunder Minimum (1645–1678), the cycle duration contracted to approximately eight years, then gradually extended to the standard length of about 11 years from 1678 to 1715. These results provide a critical historical context for present-day observations and future forecasts.

By investigating the relationship between rise time, its proportion relative to cycle length, and solar cycle intensity for cycles 0 to 24, we find that the rise time proportion value of 0.4 can effectively distinguishing between strong and weak solar cycles. The cycles of around 11 years (cycles −12, −11, −6, and −5), determined from the red equatorial aurorae, follow this rule. Notably, the rise time proportion of 0.4 is also applicable for the four cycles of eight years observed during the first half of the Maunder Minimum, revealed by the red equatorial aurora, making it possible to distinguish between the two stronger cycles (cycle −10 and −7) and the two weaker cycles (cycles −9 and −8). This result is important to understanding solar dynamics, and deserves further investigation in the future. It also suggests that the red equatorial aurora can potentially characterize the strength of solar cycles to a significant extent.

Conflict of interest

The authors declare that they have no conflict of interest.

Acknowledgments

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The ancient Korean auroral records are publicly available at Figshare (https://doi.org/10.6084/m9.figshare.14471154). The version 1 group number (Hoyt and Schatten, 1998) is publicly available at the World Data Center for Sunspot Index and Long-term Solar Observations (WDC-SILSO; https://www.sidc.be/SILSO/groupnumberv3). The GSN deduced from the active-day statistics is publicly available in Vaquero et al. (2015). The naked-eye sunspots records in the local gazetteer of China are publicly available in Xu ZT and Jiang YT (1982). The solar modulation parameter ϕ is publicly available in Brehm et al. (2021). The cycle minima and maxima dates derived from sunspot number are publicly available on NOAA (https://www.ngdc.noaa.gov/stp/space-weather/solar-data/solar-indices/sunspot-numbers/cycle-data/table_cycle-dates_maximum-minimum.txt).

Supplementary Materials

The Solar Cycles Determined from Various Datasets

Table S1 present a comparison between the solar cycles we have identified from red equatorial aurorae and those from various other sources. The cycle data from Waldmeier (1961) is estimated from the sunspot number, while that from Link (1978) is based on the auroral observations. Schove (1979) determined the cycle data from the auroral and telescopic sunspot observations. The cycle data in Beer et al. (1998) is derived from ^{10}Be concentrations in Dye 3 ice core. The cycle minima provided by Nagovitsyn (2007) is estimated from the total sunspot area index, while that from Velasco Herrera et al. (2022) is derived from a new reconstruction of group sunspot number (GSN) using algorithms from machine

Table S1. Comparison between solar cycle minima and solar cycle numbers determined in this work and other sources.

Cycle number	This work	Waldmeier 1961	Link 1978	Schove 1979	Beer 1998	Nagovitsyn 2007	Velasco Herrera 2022
−13	1610.8*?	–	1601	1598.8	1605	–	–
−12	1619*?	1610.8	1610	1608.9	1611	1609.8	–
−11	1632?	1619.0	1619	1620.2	1620	1620.5	1618
−10	1645	1634.0	1633	1633.7	1635	1633.3	1632
−9	1653	1645.0	1645	1645.5	1649	1647.0	1646
−8	1662	1655.0	1657	1655.5	1661	1656.6	1658
−7	1670	1666.0	1667	1666.7	1674	1667.3	1668
−6	1678	1679.5	1676	1679.5	1683	1681.1	1681
−5	1688	1689.5	1687	1689.5	1696	1690.7	1691
−4	1699	1698.0	1698	1699	1705	1698.6	1702
−3	1712*	1712.0	–	1712.5	1714	1712.1	1712
−2	1723.5*	1723.5	–	–	1726	1723.4	1723
−1	1734*	1734.0	–	–	1736	1733.2	1733
0	1745*	1745.0	–	–	1743	1746.0	1744
1	1755.2*	1755.2	–	–	–	1755.5	1755

Note: *The cycle minima are adopted from Waldmeier M (1961). ? The minima need further evaluation in future.

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