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Analyses for graphical records for a total solar eclipse in 1230 May: a possible reference for the 'Medieval Grand Maximum'

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ABSTRACT

Datable graphical records of total solar eclipses allow us to assess contemporaneous variability of Earth's rotation speed, solar coronal structure, and solar-wind conditions. Such graphical records were studied back to the early 18th century. Here, we examine Matthew Paris' medieval manuscript, an eyewitness account of a total solar eclipse just after local sunrise on 1230 May 14, to analyse his drawings for this eclipse. We philologically identify his observational site as St. Albans and compute local eclipse visibility. To locate St. Albans in the totality path, our analysis requires an accumulative error in time due to the variation in the Earth's rate of rotation, ΔT, in the range 394 s $< \Delta T <$ 764 s (loose scenario), slightly revising the latest published ΔT spline curve. The eclipsed Sun sould have been visible after local sunrise if we set the ΔT margins to 394 s $< \Delta T <$ 659 s (strict scenario), which requires a further slight modification of the latest ΔT spline curve. Matthew Paris' drawing of the total solar eclipse showed streamer-like structures similar to solar-minimum-type coronal streamers, consistent with the local tilt of the apparent solar equator. This is morphologically consistent with the minimum-type solar coronal streamers predicted from the open solar flux reconstructed from the ^{14}C data set. This record potentially demonstrates a similarity in solar cycles between the 'Medieval Grand Maximum' and modern solar cycles. Collectively, historical eclipse records could be used as spot references for Earth's rotation speed, solar coronal dynamics, and background solar dynamo activity on a millennial time-scale.

Key words: celestial mechanics – eclipses – Sun: activity – Sun: corona – Sun: magnetic fields – solar wind.

1. INTRODUCTION

As one of the greatest astronomical spectacles, total solar eclipses have marveled human civilizations and left their footprints in historical documents, arts, and scientific observations over millennia (De Jong & Van Soldt 1989; Stephenson 1997; Littman et al. 2009; Pasachoff & Olson 2014; Pasachoff 2017). During these astronomical spectacles, the Moon completely conceals the Sun from ground observers, to significantly darken the daytime sky, considerably reducing solar radiation to the Earth's surface, and thereby making the chromosphere and coronal streamers visible to ground-based observers (Littman *et al*. 2009; Pasachoff 2009). As such, total solar eclipses offer scientific insights into multiple scientific areas (Pasachoff 2009, 2017; Orchiston et al. 2015), including solar diameters (Morrison et al. 1988; Fiala et al. 1994), solar coronal structure (Loucif & Koutchmy 1989; Hanaoka et al. 2012), coronal mass ejections (Eddy 1974; Lockwood & Owens 2021), solar–terrestrial interactions (Harrison and Hanna 2016), and the detection of elements in the Sun, including the discovery of helium (Nath 2013).

Historical eclipse reports allow us to constrain ancient/medieval chronologies, as these astronomical spectacles occur only infrequently at a single site. This is because the apparent diameters of the Sun and the Moon roughly coincide, and their totality paths tend to form only a narrow band in each case (Espenak & Meeus 2009). Locations of the totality paths depend on the relative positions of the Sun, the Moon, and Earth and the variability of Earth's rotation speed (Stephenson 1997). This variability parameter is evaluated with ΔT, the difference between a theoretically uniform timescale (Terrestrial Time = TT) and a timescale measured with Earth's rotation (Universal Time = UT). As such, historical eclipse reports have been of significant importance to better constrain the variability of the Earth's rotation when they offer robust descriptions of the totality and their observational sites (Stephenson et al. 2016; Morrison et al. 2021; Hayakawa et al. 2022), in combnation with recent developments on the ephemeris data (Folkner et al. 2014).

Graphical eclipse records are of additional importance, as they occasionally capture solar coronal structures. These records have benefitted studies on coronal streamer dynamics in the past by serving as spot indicators for large-scale solar magnetic fields in longer time-

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scales, enabling visual comparison of both solar maxima and solar minima (Loucif & Koutchmy 1989; Vaquero 2003; Owens et al. 2017), regular solar cycles and grand solar minima (Eddy 1974; Riley et al. 2015; Hayakawa et al. 2020, 2021a). However, it is rare to find such graphical records or mentions of solar coronal structures in historical records (Stephenson 1997, p. 50). To date, in the scientific community, datable graphical records of total eclipses have been studied only back to 1706 and 1715 (Eddy 1976; Hayakawa et al. 2021a), except for an undated petroglyph that has been tentatively associated with a total solar eclipse in 1097 (Vaquero and McKim Melville, 2014). Partial eclipse drawings, on the other hand, were studied back to 1153 (Stephenson 1997, pp. 418–419). Even in textual eclipse records, coronal structures are seldom mentioned before the 18th century (Wang & Siscoe 1980; Stephenson 1997; Martínez Usó and Marco Castillo, 2022).

In this context, it is important to explore original manuscripts of historical chronicles, as they occasionally include graphical records of astronomical and celestial phenomena (Stephenson & Willis 1999; Willis & Stephenson 2001; Hayakawa et al. 2017; Uchikawa et al. 2020). Among such historical manuscripts, Matthew Paris' *Chronica Majora* is of particular interest, as it reports and interprets numerous natural phenomena, including ≈ 20 solar eclipses (Vaughan 1958, pp. 144–145 & 253–258; Hamilton 2000; Weiler 2018; Kamenzin 2022). For this chronicle, three autograph manuscripts have been preserved to date: The first (MS 26 in the Parker Library at Corpus Christi College, Cambridge) covers from the beginning down to 1188, the second (MS 16 in the Parker Library at Corpus Christi College, Cambridge) comprises years 1189–1253, and the third (Royal MS 14 C VII in the British Library) treats years 1254–1259 (folios 157 recto–231 recto) with an abridgement of the *Chronica Majora*, years c.1070–1253, known as *Historia Anglorum*. Among them, the MS 16 includes a graphical record of the total solar eclipse on 1230 May 14. This has been noted by Luard (1876, p. 195) and commented on in philological studies (James 1926, p. 12; Vaughan 1958, p. 254; Lewis 1987, pp. 208–209), whereas this graphical record seems to have been overlooked by most historians and the entire scientific community (cf. Stephenson 1997)[1].

This study aims to review Matthew Paris' graphical and textual records of the total solar eclipse on 1230 May 14 in order to contextualize these records considering the latest studies on solar–terrestrial environment. Section 2 shows these records with English translations. Section 3 identifies the observer and observational site using philological analyses. Section 4 calculates local eclipse visibility. Section 5 compares the historical records with the contemporaneous Earth's rotation variability. Section 6 analyses the probable depiction of coronal structure in comparison with the estimated open solar flux (OSF) and solar-wind variability.

2. THE RECORD

The record of the solar eclipse on 1230 May 14 is presented in MS 16 (folio 79verso; hereafter f. 79v) of the Corpus Christi College in Cambridge. The original text[2] is translated as follows:

> In the same year (i.e. 1230 CE), an extraordinary eclipse of the Sun took place in the very early morning immediately after sunrise, on the day before the Ides of May (May 15; therefore, the day before was May 14) in the Rogation days, namely the third day of the week (i.e. Tuesday); as a result, the labourers in the fields and many others, who had begun their morning's work, were obliged to leave it on account of the excessive darkness and decided to return to bed and go back to sleep. But at length, after the space of 1 h, to the astonishment of many, the Sun regained its usual brightness (Translation: the authors; cf. Giles 1849, p. 535; Lewis 1987, p. 208; Stephenson 1997, p. 425).

This text is located in the middle of the right column, along with diagrams for the solar eclipse in two steps (Fig. 1). The left diagram shows a deeply obscured solar disc with its rim in a white–yellow crescent shape and red radiating rays from the crescent. On its left side, the diagram is annotated as 'The Sun giving little or no light towards us'.[3] The central diagram shows a roundish red sun with emanating red rays. Although it apparently represents an ordinary sun, an annotation nearby describes this as "in the very early morning, the Moon in conjunction"[4] and indicates this image as the Moon hiding the solar disc or the solar disk hidden by a lunar disk in a total eclipse. Therefore, morphologically speaking, the emanating light from the eclipsed solar disc appears to represent solar coronal streamers. On the right side, the Earth darkened by the eclipse is depicted as a black disc, with the text 'the Earth (looked) like this'.[5] This text is written on the right-hand margin, with a wavy line connecting the words. At the bottom edge of that line is the following text, surrounded by a trapezoid, explaining these entire depictions: 'the morning eclipse'.[6]

3. BACKGROUND OF THE SOURCE REPORT

Philological profiles allow us to associate this text with Roger of Wendover (d. 1236). The drawings and annotations by Matthew Paris are confirmed as eyewitness accounts at St. Albans in 1230. Matthew Paris (c. 1200–1259) became a Benedictine monk at St. Albans Abbey in England (N51°45′, W000°20′) in 1217 and spent most of his life there afterwards, except for his travels to Westminster in 1247 and Norway in 1248 (Vaughan, 1958, pp. 1–20). Among Matthew's works, *Chronica Majora* covers world history from the creation to 1259, including the account and drawings of the said solar eclipse (Fig. 1; Luard 1876). Matthew's accounts on the years from the Creation to 1235 were generally dependent on *Flores Historiarum* (≈1235) written by Roger of Wendover, his fellow at St. Albans; however, Matthew sometimes revised Roger's text (Coxe 1842; Vaughan 1958, pp. 21–34; Weiler 2009). Sections after 1235 are more or less originally by Matthew Paris (Hilpert 1981; Greasley 2021). Three illuminated manuscripts of *Chronica Majora* were mostly written by Matthew's hand at St. Albans Abbey. In these manuscripts, the text is generally given in two columns and surrounded by many illustrations drawn by Matthew's own hand. The illustrations are generally associated with written text nearby, occasionally offering unique information (Lewis 1987).

Contextually, we identified Matthew Paris' source for his 1230 eclipse account as Roger of Wendover's *Flower of History*, which

[1]The partial solar eclipse on 1255 December 30 is also recorded with a drawing in the *Chronica Majora* (folio 181 recto of Royal MS 14 C VII in the British Library), which is not analysed in this study (for this record, see Luard, 1880, p. 539; James, 1926, p. 21; Lewis, 1987, pp. 292–293).

[2]*Eodem anno facta est eclipsis solis, contra morem solitum, summo mane confestim post ortum suum, pridie idus Maii, in Rogationibus, scilicet feria tertia, ita quod agricolae et alii multi, labores mane inchoatos propter nimiam obscuritatem relinquentes, stratum repetere et sese iterum sopori dare decreverunt; sed tandem, quasi post unius horae spatium, multis admirantibus, sol consuetam optinuit claritatem* (Text: Coxe, 1842, p. 211; Luard, 1876, p. 195).

[3]*Sol parum vel nichil versus nos accensus.*

[4]*summu(m) mane luna in coitu.*

[5]*Terra sic.*

[6]*Eclipsis matutinalis.*

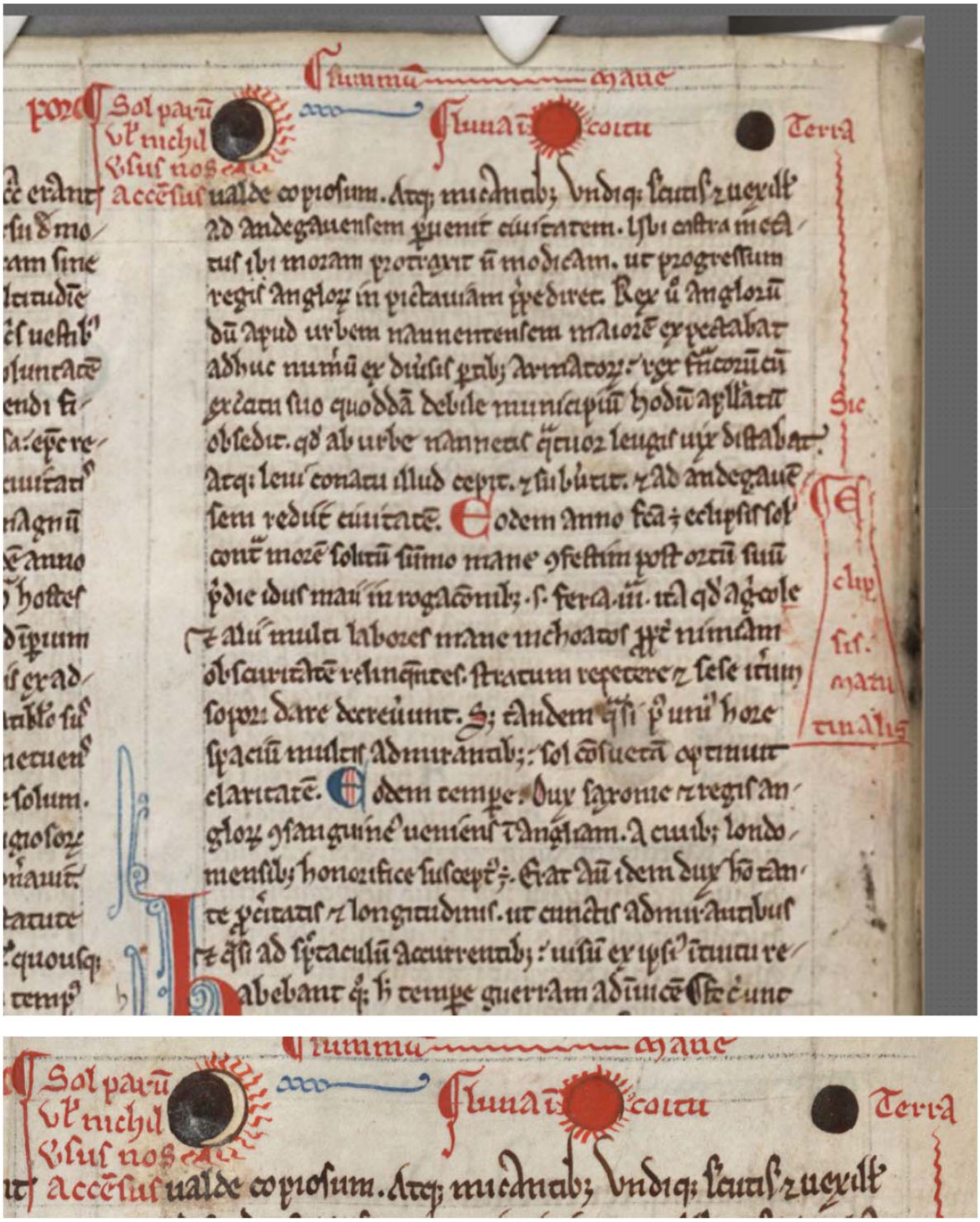

Figure 1 Text and drawing of the solar eclipse on 1230 May 14 (MS 16, Corpus Christi College, Cambridge, f. 79v, upper right side). Image courtesy of the Parker Library of the Corpus Christi College in Cambridge. Licensed under a Creative Commons Attribution-NonCommercial 4.0 International License.

Matthew Paris relied on for events before 1235 during the compilation of *Chronica Majora*. Indeed, their texts are the same as each other (Coxe 1842, p. 211; Luard 1876, p. 195; cf. Newton 1972, p. 176, whose description is inaccurate). None the less, these drawings are conceretely Matthew Paris' own autographs except those drawn at the end of the chronicle, which were intruded by his assistants (Lewis 1987, pp. 1–134). To date, previous studies have correctly associated this eclipse account with Roger of Wendover (Newton 1972, pp. 175–176; Stephenson 1997, p. 425), whereas they consider Roger in 1230 as a prior account from Belvoir and identify the observational site accordingly. However, historical studies have shown that Roger lived in St. Albans in 1230 after moving from Belvoir in 1219 (Corner 2004) or at latest by 1225–1226 (Crook 2015). Hence St. Albans in 1230 hosted both Matthew Paris and Roger of Wendover. The Abbey is most probably where they both witnessed this solar eclipse.

From these facts, we consider both Roger of Wendover's text and Matthew Paris' diagrams to be their eyewitness accounts at St. Albans. Matthew Paris' drawings and annotations indicate the

Table 1 Local eclipse visibility conditions at St. Albans on 1230 May 14, based on M + 21's ΔT spline curve (ΔT = 838 s) and our ΔT margin (ΔT = 650 s). Here, we define 'magnitude (*M*)' as $M = (r_s + r_m—d)/(2\ r_s)$, where r_s, r_m, and d represent Sun's apparent angular semidiameter, Moon's apparent angular semidiameter, and apparent angular distance of the centres of the Sun and the Moon, respectively (see Hayakawa et al., 2022). We have also defined 'obscuration' with a ratio of the eclipsed area. We also use the following abbreviations: BPSE (beginning of the partial solar eclipse), BTSE (beginning of the total solar eclipse), MTSE (maximum of the total solar eclipse), ETSE (end of the total solar eclipse), EPSE (end of the partial solar eclipse), and SR (sunrise). Altitudes are given in degrees for parameters of the solar disc without refractions. We have indicated timings at and before local sunrise with asterisks. For the local SR, we have applied atmospheric refraction of ≈34 arcmin according to the United Kingdom Hydrographic Office (UKHO, 2019, p. A12).

			ΔT = 650 s			
	LAT	Magnitude	Obscuration	Central altitude	Bottom altitude	Top altitude
BPSE	03:16:14*	0.000	0.000	− 6.34	− 6.60	− 6.08
SR	04:02:32*	0.998	0.999	− 0.83	− 1.09	− 0.57
BTSE	04:02:40	1.000	1.000	− 0.81	− 1.07	− 0.55
MTSE	04:03:22	1.005	1.000	− 0.72	− 0.98	− 0.46
ETSE	04:04:04	1.000	1.000	− 0.63	− 0.89	− 0.37
EPSE	04:52:27	0.000	0.000	5.84	5.58	6.10
			ΔT = 838 s			
	LAT	Magnitude	Obscuration	Central altitude	Bottom altitude	Top altitude
BPSE	03:13:36*	0.000	0.000	− 6.63	− 6.89	− 6.37
BTSE	03:59:46*	1.000	1.000	− 1.18	− 1.44	− 0.92
MTSE	04:00:38*	1.008	1.000	− 1.07	− 1.33	− 0.81
ETSE	04:01:31*	1.000	1.000	− 0.96	− 1.22	− 0.70
SR	04:02:32*	0.982	0.985	− 0.83	− 1.09	− 0.57
EPSE	04:49:36	0.000	0.000	5.45	5.19	5.71

eclipse as total and himself as having independent information from Roger of Wendover's. Therefore, Roger of Wendover's text and Matthew Paris's drawings have significant philological reliability as contemporaneous eyewitness accounts.[7]

4. LOCAL ECLIPSE VISIBILITY

Notably, this record describes the eclipse magnitude as 'extraordinary', the resultant darkness as 'excessive', the eclipse timing as 'immediately after sunrise', and ornamented the eclipse drawing with a radial structure – probably indicating solar coronal structure. Such descriptions are consistent with the significant darkening upon total solar eclipses (Figure 3.5 of Stephenson 1997). Orbital computations confirm that this eclipse was total and that St. Albans was reasonably close to or within the path of totality. These key features probably indicate that St. Albans witnessed a total solar eclipse with solar coronal streamers immediately after sunrise.

First, we computed local eclipse visibility at St. Albans (N51°45′, W000°20′) based on NASA JPL Ephemeris Data DE431 (Folkner et al. 2014) and modern reconstructions for the difference between terrestrial time and universal time, ΔT (Morrison et al. 2021, hereafter M + 21), following the procedures of Sôma & Tanikawa (2015). Their results are summarised in Table 1. Here, we defined local sunrise as the contact of the upper edge of the solar disc with the local horizon and considered atmospheric refraction conservatively as ≈34 arcmin according to the United Kingdom Hydrographic Office (UKHO, 2019, p. A12).

M + 21's ΔT spline curve allowed us to compute the ΔT value in 1230 as $\Delta T \approx 838$ s. On this basis, our calculation shows that St. Albans witnessed the maximum of this total solar eclipse (magnitude = 1.008) at 04:00:38 LAT (local apparent time), shortly before local sunrise at 04:02:32. In fact, without local horizon, it would have been possible to witness this total solar eclipse at St. Albans if we had set the ΔT margin in 1230 as 394 s < ΔT < 3588 s, following the procedures of Sôma & Tanikawa (2015). Even in the extreme case (ΔT = 3587 s), the total solar eclipse took place up to the altitude of −5.76° (at 03:21:24 LAT) and darkened the civil twilight (the solar altitude > −6° in altitude). This total solar eclipse should have been visible over the local horizon at St. Albans if we set the ΔT margin in 1230 as 394 s < ΔT < 764 s (loose scenario). This requires us to slightly revise the ΔT value in 1230 against that of M + 21's ΔT spline curve ($\Delta T \approx 838$ s).

Caveats must be noted here. Roger of Wendover (and Matthew Paris) described excessive darkness immediately after local sunrise. Matthew Paris drew whole a solar disk (Fig. 1). This could be reconciled under the following assumptions: (1) Roger of Wendover confused sunrise and eclipse darkness timing; and (2) Matthew Paris drew the lower part of the eclipsed solar disc using his imagination. Nevertheless, it is not immediately clear how Roger of Wendover defined local sunrise in his text.

Trusting these records, St. Albans could have witnessed the total solar eclipse on 1230 May 14 after the local sunrise. If we narrow down the ΔT margin to 394 s < ΔT < 659 s (strict scenario) this means that the total solar eclipse started literally 'immediately after sunrise' (Table 1), following the procedures of Sôma & Tanikawa (2015). If we further narrow down the ΔT margin in 1230 to 394 s < ΔT < 447 s and apply atmospheric refraction (≈34 arcmin), the entire solar disc appeared above the local horizon of St. Albans upon totality, following Matthew Paris' drawings (Fig. 1). This narrower range.

5. COMPARISON WITH ESTIMATES FOR HISTORICAL EARTH ROTATION VARIABILITY

Fig. 2 contextualizes our ΔT margins for 1230 with ΔT constraints from M + 21 and MMI16 (Martínez Usó et al. 2016). Our scenarios a slight modification of M + 21's spline curve, while these margins

[7] According to Lewis (1987: pp. 208–9, 292–3), Matthew may have intended to show the eclipse as a portent of the failure of the English campaign in France in 1230 led by Henry III of England.

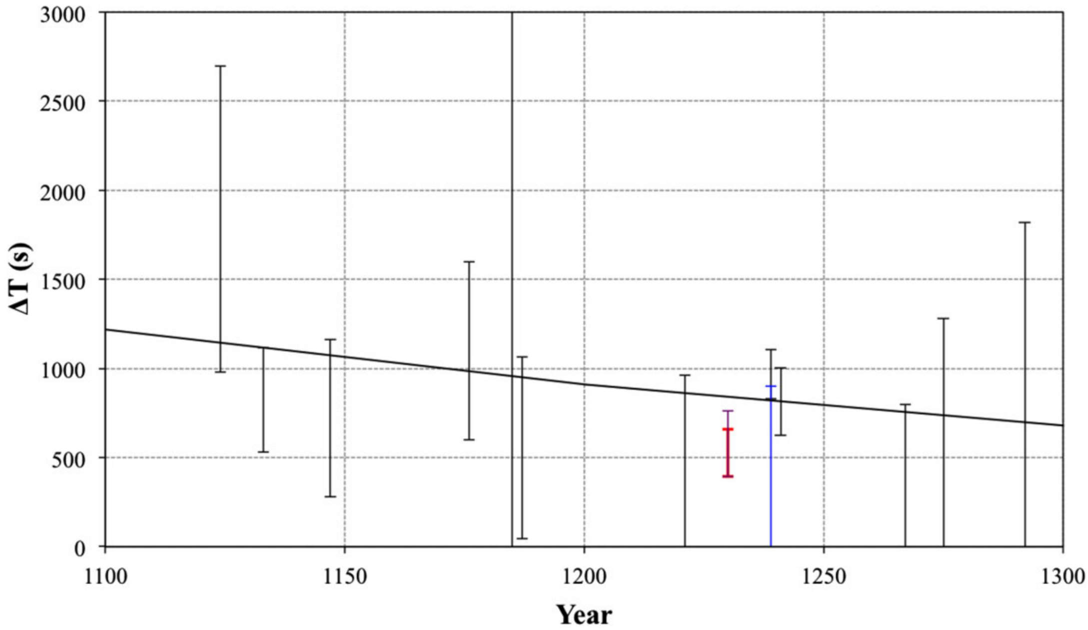

Figure 2. Our ΔT margins for 1230 compared with the existing ΔT constraints. The purple and red bars show our ΔT margins for the loose (394 s < ΔT < 764 s) and strict scenarios (394 s < ΔT < 659 s), respectively, for total eclipse visibility at St. Albans on 1230 May 14. The black and blue bars show the ΔT constraints in M + 21 and MMI16, respectively.

are largely consistent with the existing ΔT constraints in M + 21 and MMI16 and more consistent with Roger of Wendover's description and Matthew Paris' graphical presentation.

Our strict scenario can be compared with the contemporaneous ΔT constraints, when we critically reassess their source records. Fig. 2 contrasts our strict scenario with two of M + 21's ΔT constraints in 1239 and 1241. This comparison requires an upward ΔT drift of ≈ 170 s within 9 yr to 1239 but no upward drift within 11 yrs to 1241. While this seems unlikely, caveats must be noted for M + 21's ΔT constraint in 1239. M + 21 derived the lower ΔT limits from eclipse accounts in *Chronicon del Cerratense* and *Anales Toledanos Segundos*, assuming their observational sites as Cerrato and Toledo (both in current Spain), respectively. M + 21 mostly relied the European eclipse records in 1239 on Morrison et al. (2020), who reinterpreted the Spanish accounts partially based on MMI16's results. Nevertheless, MMI16 conservatively excluded the Toledo report from their ΔT evaluations, citing Stephenson (1997). MMI16 have more conservatively derived the ΔT constraint in 1239 as –570 s < ΔT < 900 s. Moreover, the source chronicle refers to events not precisely in the city of Toledo but broadly in the Kingdom of Toledo in the central Iberian Peninsula. Indeed, the observational location of the eclipse is not specified in the chronicle (Maíllo Salgado 1989; Martín-Cleto 1993; Jerez 2004). Therefore, for the ΔT margin in 1239, it is probably safer to consider the eclipse account from *Anales Toledanos Segundos* as not strictly from the city of Toledo and follow MMI16's more conservative ΔT constraint with greater uncertainty. Overall, we cannot completely reject our strict scenario considering contemporaneous ΔT constraints. Meanwhile, the solar disk under total eclipse was probably not entirely visible over the local horizon, as this condition (394 s < ΔT < 447 s) requires a notable upward ΔT drift (≈ 180 s) within 11 yrs by 1241.

Here, we have a base assumption to locate St. Albans at the sea level in a flat plain. However, in reality, St. Albans had the old town area in the 13th century around a top of one of local hills (e.g., altitude of ≈103 m above sea level for the floor of the abbey (Perkins 1903, p. 115)). This altitude indicates a slightly better view for the sunrise eclipse from here. Moreover, Matthew Paris should have had an access to the abbey tower that had been constructed by the 12th century and had an altitude of ≈ 44 m (Perkins 1903, p. 115). On their basis, the total solar eclipse should have been more easily visible. Owing to these topographical benefits, Matthew Paris might have been able to see the entire solar disk under total solar eclipse, whose bottom was at best 1-2° below the local horizon even from the sea level (Table 1). As such, we cannot exclude the possibility for Matthew Paris to have actually witnessed the entire solar disk over the local horizon and depicted the solar disk under total solar eclipse without relying on additional imaginations.

6. PICTORIAL PRESENTATION AND IMPLICATIONS OF THE PROBABLE SOLAR CORONAL STREAMERS

Notably, one of Matthew Paris' eclipse drawings shows 'ray' structures around the eclipsed Sun. The solar disc is depicted in a reddish colour, with Matthew Paris' annotation indicating this image as an eclipsed Sun. For some reason, Lewis (1987, pp. 292–293) described this image as 'a totally eclipsed black solar disc with tiny red rays', seemingly indicating a mis-selection of the disc colour or later overlay of the reddish colour over the blackish/blank disc.

Qualitatively, the reddish 'ray' structures appear consistent with solar coronal streamers. The streamer-like structures appear shorter on the upper left and lower right and longer on the lower left and upper right (Fig. 3a). In this context, it is of interest to check the chronological context of this total solar eclipse upon reconstructions of the solar coronal streamers.

We computed the heliographic coordinates during the local maximum of this total solar eclipse in Fig. 3(b). Our calculation shows that the apparent solar axis is slightly inclined westward from the local zenith and solar equator from the lower left to the upper right. Comparatively, Fig. 3 shows that the depicted orientations of the longer streamers from the eclipsed Sun (Fig. 3a) are broadly

Figure 3 Matthew Paris' drawing of a total solar eclipse on 1230 May 14 (MS 16, Corpus Christi College, Cambridge, f. 79v, upper right side) and our calculation of the heliographic coordinate at the maximum of this total solar eclipse following procedures in Hayakawa et al. (2021b). The left image is shown courtesy of the Parker Library of Corpus Christi College in Cambridge. Licensed under a Creative Commons Attribution-NonCommercial 4.0 International License.

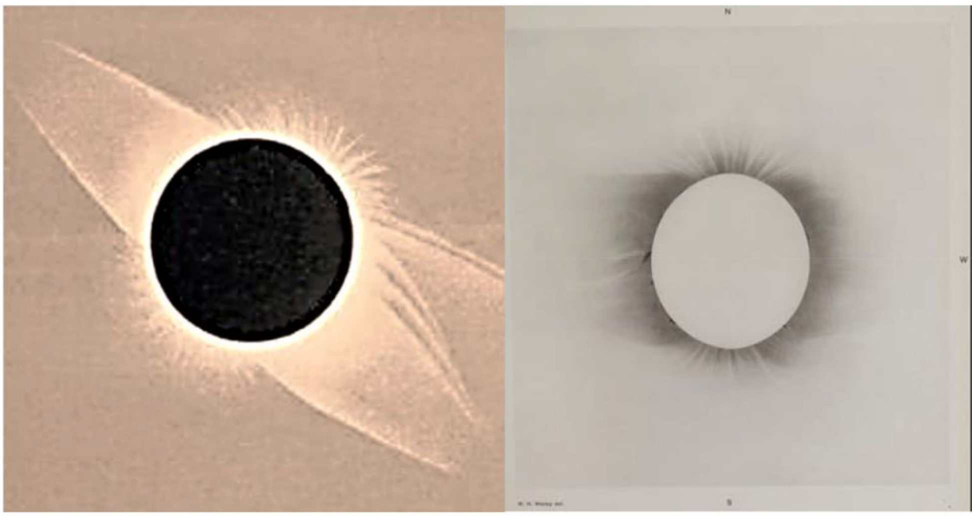

Figure 4 Two total solar eclipse cases on 1878 July 29 (courtesy of © the Royal Society Archives) and 1901 May 18 (Plate VII of Dyson 1927).

consistent with the calculated orientations of the solar equator at the time of the total solar eclipse.

To help interpret the eclipse observations, we resorted to observationally constrain modelling of the coronal magnetic field. We tested methodological validity using two cases of total solar eclipses on 1878 July 29 by Admiral William Harkness at Creston, Wyoming, USA and 1901 May 18 by William Henry Wesley at Pamplemousses, Mauritius (Plate VII of Dyson 1927), as shown in Fig. 4. We used Sunspot Number version 2 (SILSO SSN v2; Clette & Lefèvre 2016) as an input parameter to predict OSF (the solar magnetic field component carried by solar wind out into interplanetary space), streamer-belt width, inclination, and streamer-belt predictions, using the methods and coefficients of Lockwood & Owens (2014), where the loss rate coefficient is adjusted according to SILSO SSN v2 (Clette & Lefèvre 2016), as shown in Figs 4 and 5 are consistent with one another, and this result confirms the validity of Lockwood and Owens' model (2014).

For the 1230 total solar eclipse, we did not have the SILSO SSN v2 data, as this eclipse took place centuries before the earliest accounts of telescopic sunspot observations (Arlt & Vaquero 2020). Therefore, instead of SILSO SSN v2, we used ^{14}C estimates of OSF for our observational input. Here, we used the recent OSF reconstruction (Usoskin et al. 2021), shown in the top panel of Fig. 6, with upper and lower bounds taken to be ± 1σ uncertainty. It can be seen that 1230 was a time of low OSF and towards the end of a weak 11-yr cycle in this property. While Usoskin et al. (2021) provide an inversion of OSF to sunspot number (SSN), it can result in (unphysical) negative SSNs during times of very low OSF, such as the period of interest (though they are typically consistent with zero SSN within uncertainty). Thus, instead, we used a physically constrained model of OSF (Owens and Lockwood 2012) to determine SSN. This method is described in more detail in Owens et al. (2023).

The results are shown in the second panel of Fig. 6. As expected from the OSF series, SSN reconstruction similarly suggests that 1230 is near the end of a very weak solar cycle, with a peak SSN of 40 (ranging from 67 to 15). The low values of OSF and SSN during this cycle mean that the start and end dates of the cycle (and hence the solar cycle phase of 1230) are difficult to determine

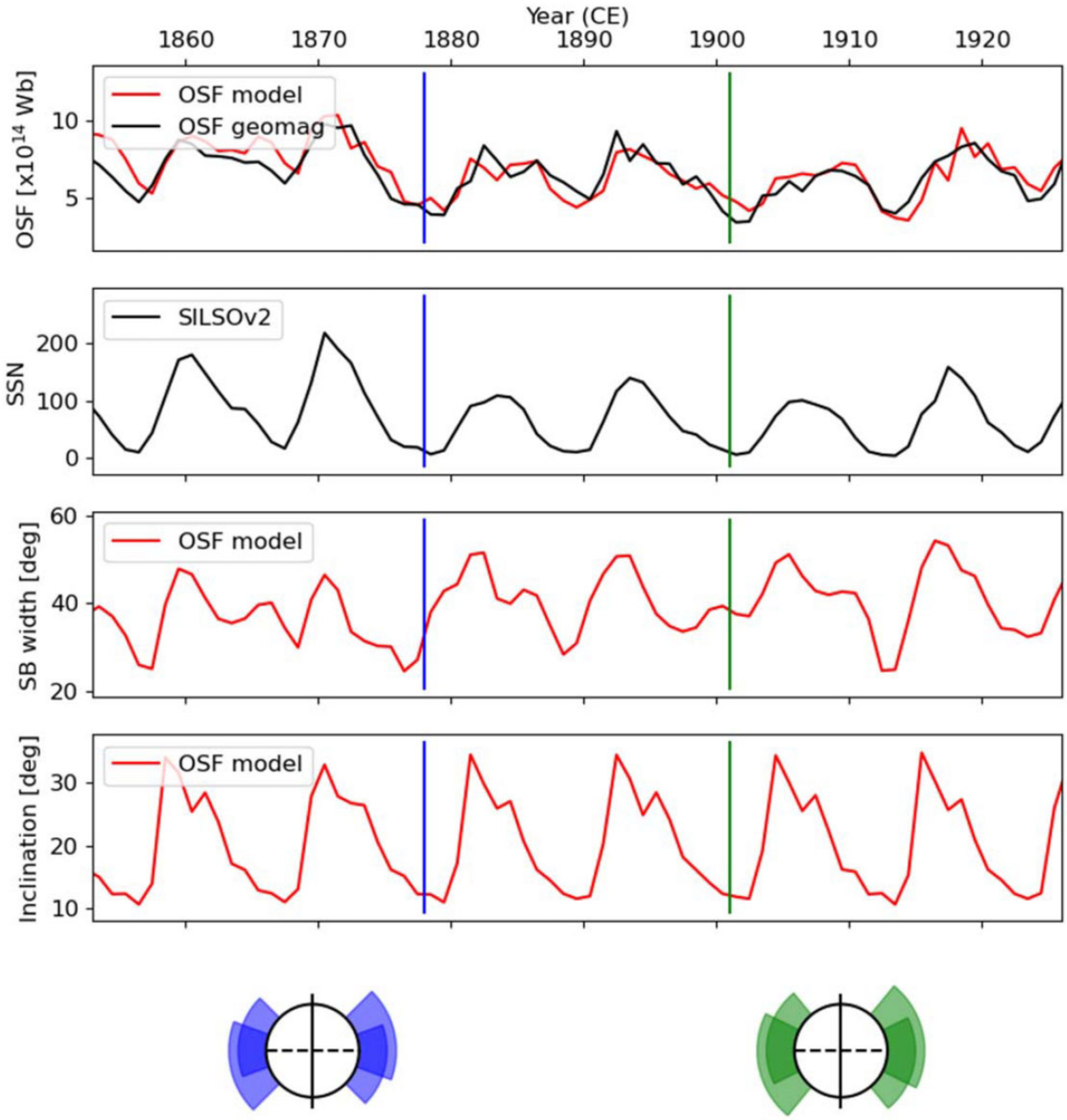

Figure 5 Chronological contexts of the total solar eclipses in 1878 (blue) and 1901 (green) based on OSF in the first panel, SSN in the second panel, streamer-belt (SB) width, inclination, and SB predictions with the best, upper, and lower OSF estimates from SILSO SSN v2 (Clette & Lefèvre 2016) using the methods and coefficients of Lockwood & Owens (2014), where the loss rate coefficient is adjusted according to SILSO SSN v2 (Clette & Lefèvre 2016).

precisely, even before accounting for uncertainty in the ^{14}C record itself. Nevertheless, applying the method of Lockwood & Owens (2014) and Owens et al. (2017) to the reconstructed SSN and solar cycle start dates, we obtained the streamer belt width estimate shown in the third panel and the streamer belt inclination angle shown in the fourth panel. The proximity to the solar minimum implies that the expected inclination of the streamer belt to the rotational axis is low (≈15°). However, contrary to expectations for a typical solar minimum corona, the low OSF value means that the polar coronal-hole flux remains weak, and thus the streamer belt remains fairly broad, between 30° and 50° (cf. 15° to 20° during the 1986 and 1996 solar minima in Figure 8 of Lockwood & Owens 2014).

Caveats must be noted for the chronological uncertainty. For the period of 1700–1900 where there is overlap between ^{14}C and sunspot records, the long-term (e.g. 11-yr smoothed) variations are very well matched. At the annual time-scale, the timing of solar cycles generally matches to within a year or two (Usoskin et al. 2021). However, there are individual cycles, most notably around 1760, where ^{14}C and SSN variations are almost in antiphase. The cause of this discrepancy is not well understood, and we cannot know when similar errors are present before the onset of telescopic sunspot observations in 1610. Thus, the interpretations presented here should be treated with caution – they represent the best estimate from the current available data. Indeed, eclipse observations may be one of the few ways to provide validation of the ^{14}C reconstructions prior to 1610.

At the bottom of Fig. 6 are schematics of the expected streamer belt width and orientation for the best, upper, and lower ^{14}C OSF estimates. The solid black line shows the solar rotation axis as viewed from St Albans in 1230 May, with the dashed line showing the solar equator. The centre of the streamer belt can be displaced from the solar equator by up to +/− the inclination angle over a solar rotation. These two extremes of the streamer belt position are shown as shaded areas. By morphology, this coronal structure (see bottom panel of

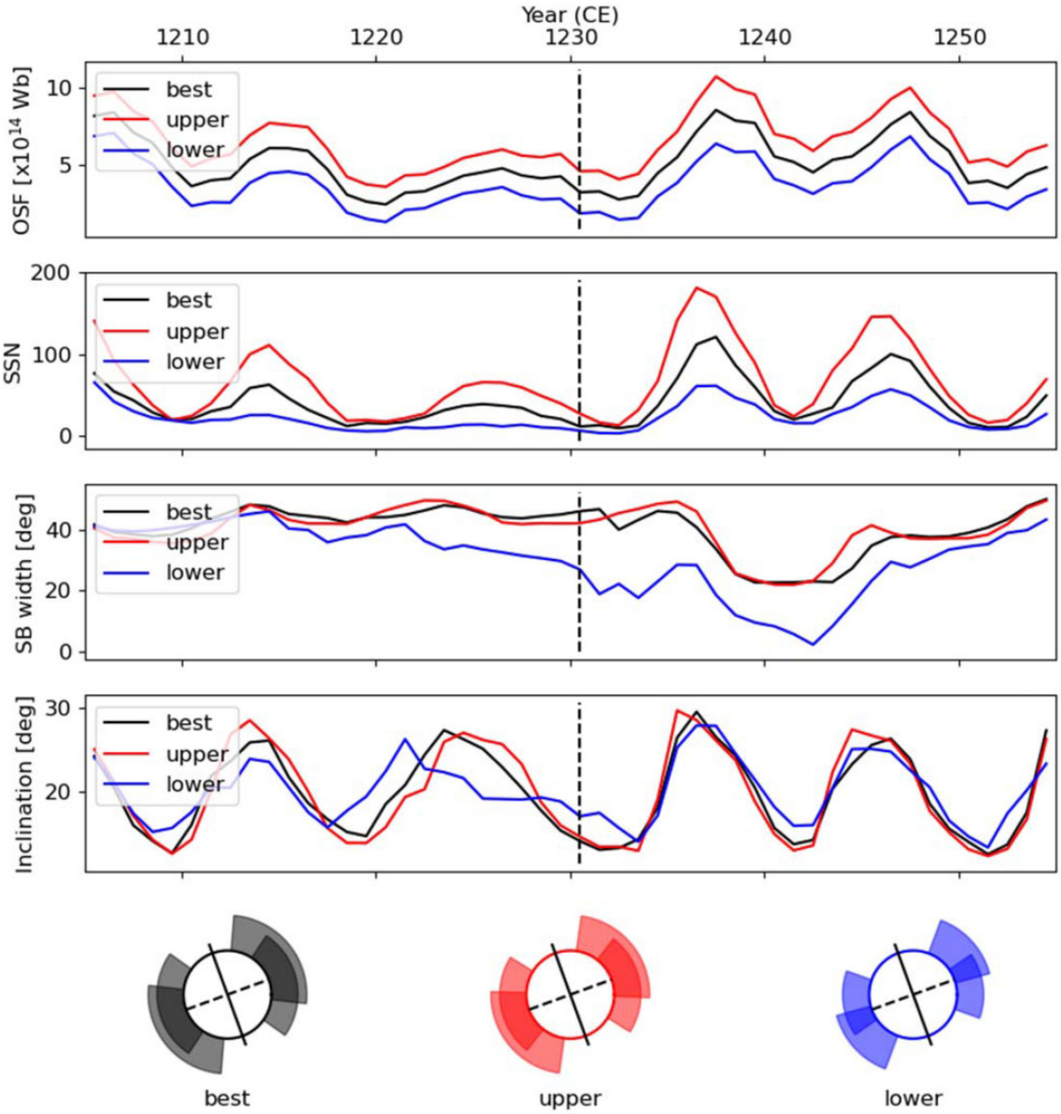

Figure 6 Chronological contexts of the total solar eclipse in 1230 (broken black line) based on OSF in the first panel, inferred SSN in the second panel, streamer-belt (SB) width, inclination, and SB predictions with the best, upper, and lower OSF estimates from ^{14}C data (Usoskin et al. 2021) using the methods and coefficients of Lockwood & Owens (2014), where the loss rate coefficient is adjusted according to SILSO SSN v2 (Clette & Lefèvre 2016).

Fig. 6) is consistent with Matthew Paris' graphical presentation for the eclipsed Sun with shorter streamers on the upper left and lower right and longer streamers on the lower left and upper right (Fig. 3a). In this case, Matthew Paris' eclipse drawing should have shown a substantial K-corona and large-scale magnetic field in 1230.

7. CONCLUSION

This study examined Matthew Paris' account and drawings of the total solar eclipse on 1230 May 14 in *Chronica Majora* (Fig. 1). We profiled the philological backgrounds of this account, confirming that the textual report was derived from John of Wendover and clarified that both were probable eyewitnesses of the said total solar eclipse in 1230 at St. Albans.

We analysed the local eclipse visibility conditions at St. Albans on this date. Our calculations confirmed the visibility of this total solar eclipse based on a ΔT margin of 394 s < ΔT < 764 s (loose scenario; Fig. 2), slightly revising the latest ΔT reconstruction (M + 21). However, John of Wendover's text shows that the Sun was totally eclipsed 'immediately after sunrise'. If we take this description at face value, they further constrain the ΔT margin to 394 s < ΔT < 659 s (strict scenario; Fig. 2).

Our scenarios required a downward ΔT modification from M + 21's ΔT spline curve. However, critical assessments confirmed our strict scenario as comparable with MMI16's conservative ΔT constraint in 1239 (Fig. 3). These two scenarios allow us to further constrain the historical ΔT variations in the first half of the 13th century.

On a broader time-scale, this eclipse occurred during the so-called Medieval Grand Maximum in 1100–1250 (e.g. Lean 2018), whereas this classification does not have a full consensus of the scientific community (e.g. Usoskin 2023). In this interval, Matthew Paris' eclipse drawing shows structure that seems consistent solar coronal streamers of a solar-minimum type in 1230.

Our results emphasize a similarity of the solar coronal structures near the cycle minimum (1230) in the 'Medieval Grand Maximum' with those in modern solar cycles (Fig. 6), unlike those of the Maunder Minimum (Riley et al. 2015; Hayakawa et al. 2021b). These descriptions are broadly consistent with the OSF model based on ^{14}C data sets. As such, Matthew Paris' eclipse drawing offers a snapshot of the 'Medieval Grand Maximum' and qualitatively supports the OSF models on a millennial time-scale. Case studies on similar historical eclipse records might potentially benefit future assessments not only on the Earth's rotation speed (Stephenson et al. 2016; M + 21) but also on solar coronal dynamics and background solar dynamo activity on a millennial time-scale (Virtanen et al. 2019; Charbonneau 2020; Petrovay 2020; Karak 2023; Pevtsov et al. 2023; Usoskin 2023).

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DATA AVAILABILITY

Matthew Paris' original manuscript is preserved as MS 16 in Corpus Christi College, Cambridge (https://parker.stanford.edu/parker/catalog/qt808nj0703), licensed under a Creative Commons Attribution-NonCommercial 4.0 International License. We have derived the astronomical ephemeris data from NASA JPL DE431 (Folkner et al. 2014), the ΔT data sets from Morrison et al. (2021), the International Sunspot Number from the WDC SILSO, and the annual ^{14}C data set in 971–1900 from Brehm et al. (2021) and Usoskin et al. (2021).

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