The solar corona during the total eclipse on 1806 June 16: graphical evidence of the coronal structure during the Dalton minimum

Article

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2   **The Solar Corona during the Total Eclipse on 16 June 1806:**

3   **Graphical Evidence of the Coronal Structure during the Dalton**

4   **Minimum**

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16

17   **Abstract**

18   Visible coronal structure, in particular the spatial evolution of coronal streamers, provides

19   indirect information about solar magnetic activity and the underlying solar dynamo. Their

20   apparent absence of structure observed during the total eclipses of throughout the

21   Maunder Minimum has been interpreted as evidence of a significant change in the solar

22   magnetic field   from that during modern cycles. Eclipse observations available from the

23   more recent Dalton Minimum may be able to provide further information, sunspot activity

24   being between the levels seen during recent cycles and in the Maunder minimum.   Here,

25   we show and examine two graphical records of the total solar eclipse on 1806 June 16,

26   during the Dalton minimum. These records show significant rays and streamers around

27   an inner ring. The ring isestimated to be $\approx 0.44\ R_\odot$ in width and the streamers in excess

28   of $11.88\ R_\odot$ in length. In combination with records of spicules or prominences, these

29   eclipse records visually contrast the Dalton Minimum with the Maunder Minimum in

30   terms of their coronal structure and support the existing discussions based on the sunspot

31   observations. These eclipse records are broadly consistent with the modelled phase of

32   open solar flux and the reconstructed slow solar wind at most latitudes.

33

1. Introduction

Variability of the solar magnetic field has been directly monitored for ≈ 4 centuries with sunspot observations as a visual manifestation of magnetic flux (Clette *et al*., 2014; Arlt and Vaquero, 2020). These observations show the regular Schwabe cycle of ≈ 11 years and two longer-term intervals with significantly suppressed solar activity: most prominently, the Maunder Minimum (hereafter MM; *c*., 1645 – 1715) and, to a somewhat lesser extent, the Dalton Minimum (hereafter, DM; *c*., 1797 – 1827) (Hathaway, 2015; Muñoz-Jaramillo and Vaquero, 2019). While a number of additional intervals with comparable solar activity have been identified over millennial time scales using proxy reconstructions with the cosmogenic isotopes (Usoskin *et al*., 2007; Inceoglu *et al*., 2015), only the MM and DM can be investigated with direct observations and measurements (Usoskin *et al*., 2015; Hayakawa *et al*., 2020).

The physical nature of these two intervals, the MM and the DM, is of great interest as grand minima are generally associated with a different state of the solar dynamo (Charbonneau, 2010). Analyses of these intervals are difficult, due to their poor observational coverage relative to the modern era, there being fewer observers with poorer equipment and without the knowledge to record the most interesting aspects of the Sun frm the point of view of modern science (Arlt and Vaquero, 2020). Nevertheless, thorough analyses on the original observations have revealed their differences in terms of their solar-cycle amplitude and length, as well as sunspot distributions and highlighted their probable difference, although the poor observational coverage still prevents definitive conclusions (Eddy, 1976; Ribes and Nesme-Ribes, 1993; Usoskin *et al*., 2015; Hayakawa *et al*., 2020).

In this regard, the solar coronal structure is of significant interest, forming a visual representation of the large-scale solar magnetic field, and with the solar coronal holes providing a visual estimate of the extent of the fast solar wind source regions. In the typical solar cycles of the modern era, the polar coronal holes reach maximum areal extent around the minima to concentrate the coronal streamers nearer the solar equator, whereas the polar coronal holes shrink and even disappear around the maxima, with streamers extending to all latitudes (Figure 1). On this basis, they serve as a basis to reconstruct the large-scale solar magnetic field and the hence that of the global solar wind (*e.g.*, Loucif

1   and Koutchmy, 1989; Marsch, 2006; Lockwood and Owens, 2014; Hathaway, 2015;

2   Owens *et al*., 2017).

3

4   Both the MM and DM occurred long before the use of artificial coronagraphs which can

5   reveal the coronal structure by blocking the bright solar disc. Such structures, however,

6   can be revealed during total solar eclipses, when the Moon entirely hides the Sun and shut

7   out most of its brightness. On such occasions, the brightness of the coronal streamers is

8   visually captured (Figure 1; see also Eddy, 1976; Woo, 2019) and their extent provides

9   valuable insight on the large-scale solar magnetic field (Owens *et al*., 2017). As the visual

10   corona, as in unpolarised light, is a mixture of electron-scattered K-corona and dust-

11   scattered F-corona, extension of the K-corona is constrained by the structured solar

12   magnetic field but F-corona appears structureless, free from such constraints.

13

14

1

2   Figure 1: Ken'ichi Fujimori's drawings of the total eclipses and associated corona on

3   1991 July 17 at Lapaz in Mexico (above) and 2009 July 22 near Iou Island in Japan

4   (below). Images courtesy of Ken'ichi Fujimori. The 1991 eclipse is situated near the

5   maximum of Solar Cycle 22 and the 2009 eclipse near the minimum of Solar Cycle 23/24

6   (see Hathaway, 2015).

7

8   Therefore, the coronal structure of the MM has attracted much scientific interest.

9   Contemporary eclipse records have been intensively investigated and have shown the

10   halo-shaped corona without significant streamer structure (Eddy, 1976; Riley *et al*., 2015).

11   Eddy (1976) speculated about a total loss of the solar magnetic field during the MM.

12   Conversely, the continuation of solar cycles have been inferred from sunspot records and

13   cosmogenic isotopes (Cliver and Ling, 2011; Lockwood *et al*., 2011; Owens *et al*., 2014;

14   Vaquero *et al*., 2015) and a report of a solar spicule or prominence during the 1706 eclipse

15   (Foukal and Eddy, 2007), show that the large-scale solar magnetic field survived, even if

16   its magnitude was greatly diminished (Cliver and Ling, 2011; Riley *et al*., 2015;

17   Hayakawa *et al*., 2020).

18

19   In this context, the coronal structure in the DM is also of significant interest. However,

20   eclipse reports in this period (*c.*, 1797 – 1827) have yet to be analysed with a view to

21   understanding the large-scale solar magnetic field. Fortunately, this interval was host to

1   significant developments in scientific understanding for the solar corona.   Giovanni
2   Cassini (1706) described a "crown" (in Latin or Spanish "Corona") of light around the
3   eclipsed Sun which was often seen but given other names. He attributed it to Zodiacal
4   light.   From observing the eclipse on 22 May 1724, Giacomo Filippo Maraldi concluded
5   that the "aura" (as he called the corona) is part of the Sun because the Moon traverses the
6   corona during an eclipse; however others, such as Edmond Halley, viewing the eclipse of
7   1715 interpreted it as being caused by a lunar atmosphere, a view that had been common
8   for many years.   That debate remained unresolved until the work of José Joaquín de
9   Ferrer (1809a, 1809b, 1809c), who recorded the total eclipse on 1806 June 16. It was the
10   extended nature of the glow around the eclipsed Sun that made the   previously
11   hypothesised association with an extended lunar atmosphere highly unlikely (Vaquero
12   and Vázquez, 2009), a fact that had concerned Halley but not caused him to diverge from
13   the then-accepted theory   From the work of Ferrer the name "corona" was established as
14   was the fact that it was part of the Sun Moreover, de Ferrer was not a lone observer.
15   Simeon de Witt (1809) also observed this eclipse and cited another graphical record.
16   Situated in the midst of the DM, these records provide valuable visual evidence for the
17   large-scale solar magnetic field. Therefore, we have conducted investigations on the
18   eclipse records at that time, evaluated the reported coronal extents, and compare them
19   with contemporary observations of sunspot number, as well as modelled reconstructions
20   of the open solar flux, heliospheric modulation potential, and solar wind speed as a
21   function of latitude and time.
22

23   **2. Observations**
24   The total eclipse on 1806 June16 started from the coast of California, came across the
25   central United States and the northern Atlantic Ocean, and ended in the Western Africa.
26   Figure 2 shows its totality path, assuming the ΔT (difference of the terrestrial time and
27   universal time) as 16.3 seconds (Stephenson *et al*., 2016). As shown here, New England
28   was favourably situated in this totality path and two notable eclipse drawings were
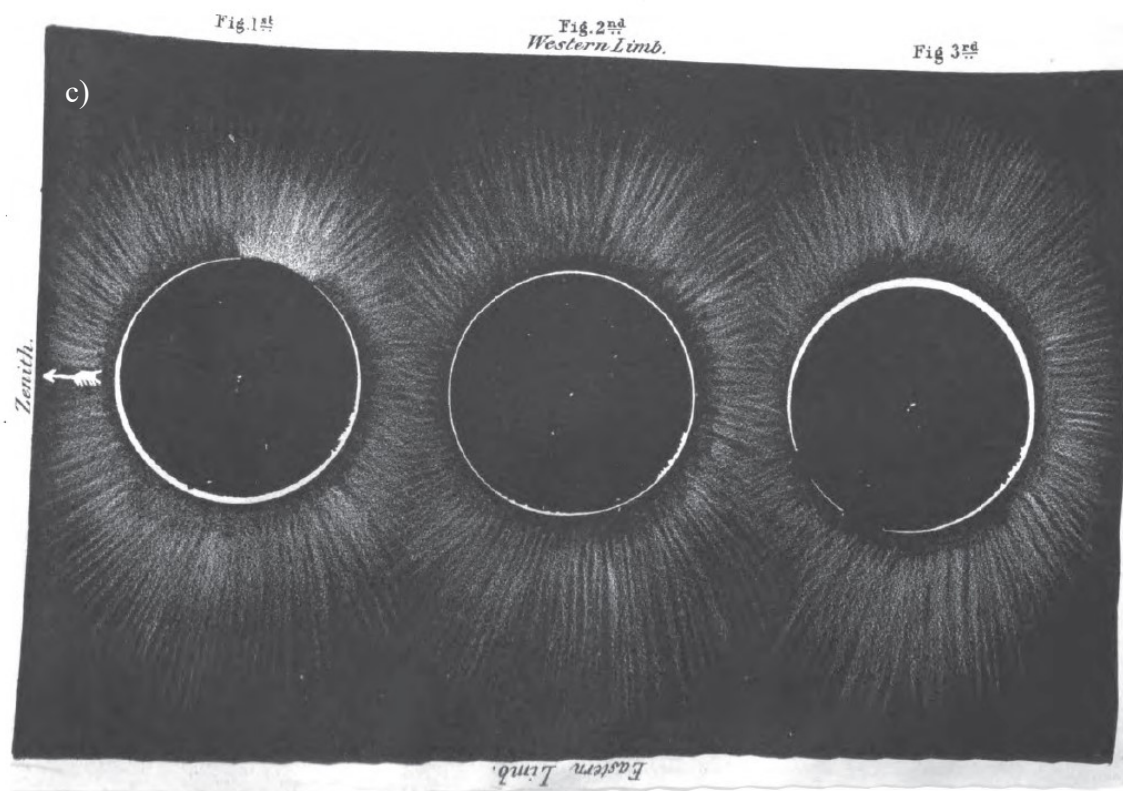29   recorded for this eclipse (see Figure 3).
30
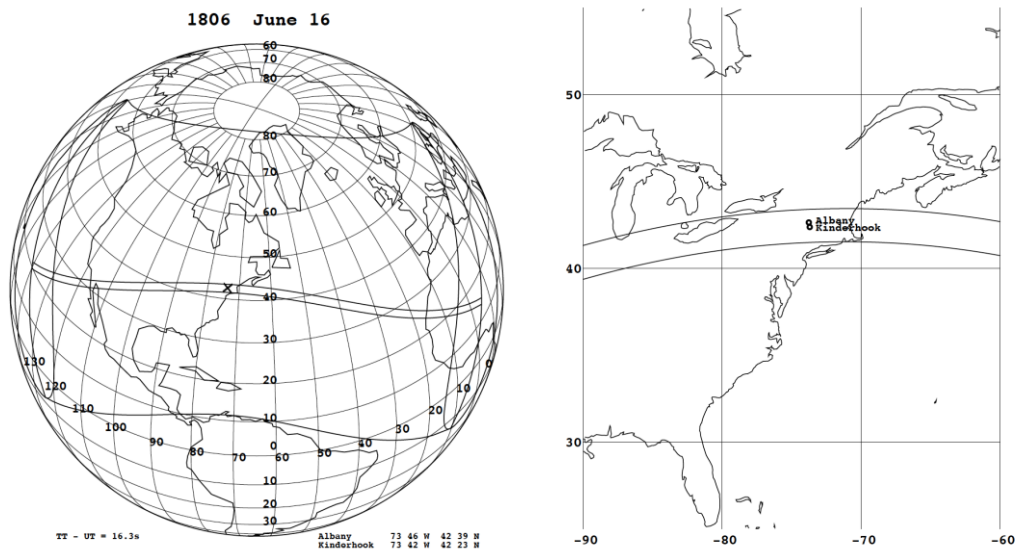
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2 Figure 2: Totality path of the total eclipse on 1806 June 16, assuming the $\Delta T = 16.3$ second

3 (Stephenson *et al.*, 2016) and its enlargement in the Eastern Coast of the United States.

4 Albany and Kinderhook are marked in these maps.

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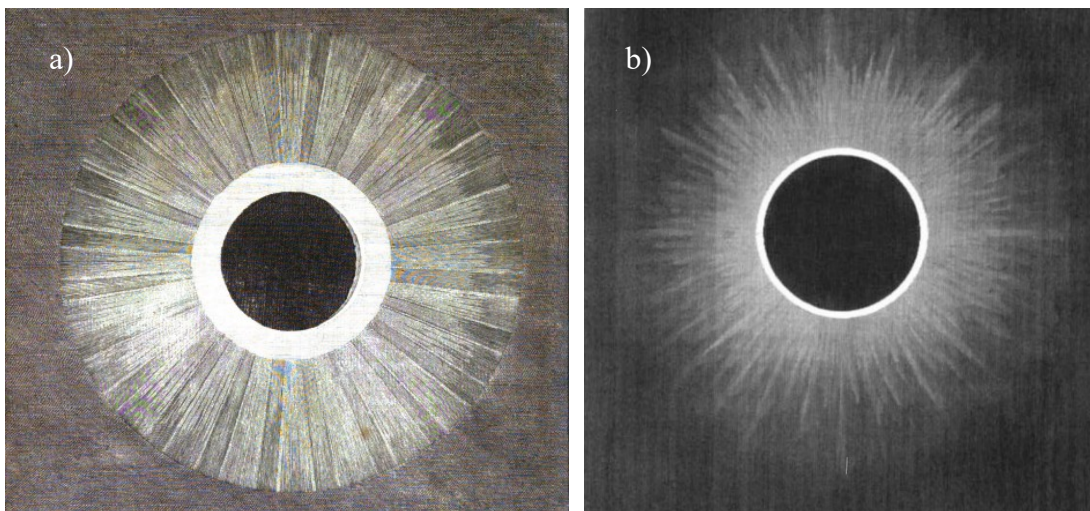
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2 Figure 3: Total eclipse drawings on 1806 June 16; (a) Don José Joaquín de Ferrer's eclipse
3 drawing reproduced from de Ferrier (1809, Plate VI, Figure 1); (b) and (c) Ezra Ames's
4 eclipse drawings reproduced from de Witt (1852, Plate 3).
5
6 The first drawing is the oft-mentioned drawing of Don Jose Joaquin de Ferrer at
7 Kinderhook (N42°23′, W73°42′. See Figure 3a). The drawing slightly emphasises the
8 eclipsed Sun more than the oft-cited drawing in Todd (1894, p. 115). De Ferrer used an
9 achromatic telescope, a circle for reflection, an Arnold chronometer, and a darkened glass
10 (De Ferrer, 1809a, pp. 265 – 266). He described the eclipse thus; "the disk had round it a
11 ring or illuminated atmosphere, which was of a pearl colour, and projected 6' from the
12 limb, the diameter of the ring was estimated at 45'. ... From the extremity of the ring,
13 many luminous rays were projected to more than 3 degrees distance. The lunar disk was
14 ill defined, very dark, forming a contrast with the luminous corona; with the telescope I
15 distinguished some very slender columns of smoke, which issued from the western part
16 of the moon. The ring appeared concentric with the sun, but the greatest light was; in the
17 very edge of the moon, and terminated confusedly at 6' distance. [At] 11:00, [I] observed
18 the appearance of a ribbon or border, similar to a very white cloud, concentric with the
19 sun, and which appeared to me to belong to its atmosphere, 90° to the left of the moon".

1 (De Ferrer, 1809a, pp. 266 – 267).

2

3 He emphasised the luminous ring around the eclipsed Sun: "Fig. 1 in Plate VI [NB our

4 Figure 3a], represents the total eclipse, I shall only remark, that the luminous ring round

5 the moon, is exactly as it appeared in the middle of the eclipse, the illumination which is

6 seen in the lunar disk, preceded 6″ 8 the appearance of the first rays of the sun" (De Ferrer,

7 1809a, p. 274). "It has appeared to me, that the cause of the illumination of the moon, as

8 noticed above, is the irradiation of the solar disk, and this observation may serve to give

9 an idea of the extension of the luminous corona of the sun" (De Ferrer, 1809a, p. 275).

10

11 This eclipse was also observed at Albany (N42°38′42″, W73°46′), where Ezra Ames

12 painted and Simeon de Witt recorded its detail (Worth, 1866, p. 41). Ezra Ames was "an

13 eminent portrait painter", as described by de Witt (1809, p. 300). His drawing was

14 attached to de Witt (1809) and deposited in the Hall of the American Philosophical Society.

15 Later on, his drawing has been involved in de Witt (1852, Plate 3) with a sequence of

16 drawings, as shown in Figures 3b and 3c.

17

18 **3. Results**

19 These diagrams look consistent with each other, showing a brighter inner ring and the

20 outer luminous rays or streamers all around the eclipsed Sun. Indeed, de Witt (1809, p.

21 300) emphasised its similarity with de Ferrer's drawing at Kinderhook. Observing from

22 the same town, de Witt (1809) described his observations as: "The edge of the moon was

23 strongly illuminated, and had the brilliancy of polished silver. No common colours could

24 express this; I therefore directed it to be attempted as you will see, by a raised silvered

25 rim, which in a proper light, produces tolerably well, the intended effect" (De Witt, 1809,

26 p. 300); and "The luminous circle on the edge of the moon, as well as the rays which were

27 darted from her, were remarkably pale, and had that bluish tint, which distinguishes the

28 colour of quick-silver from a dead white" (De Witt, 1809, p. 301). De Witt's description

29 of the colour is interesting as it fails to mention any red colour, which had been reported

30 in the 1706 eclipse by Captain Stannyon and by Wurzelbau (1706), and which reveals

31 magnetic field in the cromosphere.

32

33 The extent of the eclipse features is detailed in de Ferrer's report, along with their

1 characteristics. The brighter inner ring reportedly extended $\approx 6'$ with a colour of silver or

2 pearl. The luminous rays had dimmer colour and reportedly extended from the inner ring

3 with a distance of $\geq 3°$. Although slightly stylised, their illustrations show the bright inner

4 ring and the outer radiation (Figure 3). The breadth of the outer radiation is particularly

5 notable. The inner and outer rings are probably best interpreted as lower solar atmosphere

6 and the outer corona with streamers, respectively. Moreover, de Ferrer's description on

7 "very slender columns of smoke, which issued from the western part of the moon" implies

8 his observations on prominences or solar spicules (see *e.g.*, Beckers, 1968; Mackay *et al.*,

9 2010).

10

11 The detailed reports on the visual extents of the inner ring and outer rays allow us to

12 estimate their absolute extents. During the 1806 eclipse, the distances of the Sun and the

13 Moon from Kinderhook were estimated as ≈ 1.0161892 au and ≈ 0.0023920 au with JPL

14 DE430. Hence solar radius $R_\odot$ and lunar radius would span 15'44" and 16'42" in the sky,

15 respectively. The maximal magnitude[1] at Kinderhook is calculated as ≈ 1.028, whereas

16 this is calculated as ≈ 1.030 at the center-line near Kinderhook. Accordingly, the reported

17 extent of the inner ring of $\approx 6'$ from the lunar disk implies its absolute extent from the

18 solar disk as $\approx 0.44\,R_\odot$, considering the difference of lunar and solar radii of 58". Likewise,

19 the reported extent of the outer rays of $\geq 3°$ from the limb of this inner ring implies its

20 absolute extent from as $\geq 11.88\,R_\odot$.

21

22 **4. Discussion**

23 One of the striking common features of the eclipse reports is the coronal streamers all

24 around the eclipsed Sun, captured both descriptively and graphically (Figure 3). This

25 feature agrees well with the solar-maximum-type coronal structure (see *e.g.*, Figure 1a).

26 This supports the existence of a substantial the K-corona and hence large-scale solar

27 magnetic field, even in the midst of the DM, unlike the records of the eclipse during the

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[1] Here the magnitude of eclipse is defined by $(R_\odot + R_\eclipse - d)/(2\,R_\odot)$ where $R_\odot$ is the apparent angular radius of the Sun, $R_\eclipse$ is the apparent angular radius of the moon, and d is the apparent angular distance between the centers of the Sun and the Moon. In the case of partial solar eclipses the magnitude is equal to the fraction of the Sun's diameter obscured by the Moon. In the case of total solar eclipses the magnitude is equal to 1 at the instants of the beginning and end of the total solar eclipses and varies continuously with time.

1   MM (Eddy, 1976; Riley *et al*., 2015). On this basis, the DM could be considered in a

2   similar state of the solar dynamo, only with reduced amplitude in comparison with the

3   modern solar cycles, unlike the MM (*e.g*., Riley *et al*., 2015). This interpretation agrees

4   with the existing discussion of the amplitude and duration of the solar cycles, as well as

5   the sunspot distributions in the DM (Hayakawa *et al*., 2020), in comparison with those of

6   the MM (Eddy, 1976; Ribes and Nesme-Ribes, 1993; Usoskin *et al*., 2015).

7

8   As shown in Figure 4, this eclipse occurred in the declining phase of SC 5, which peaked

9   in 1805 February in smoothed monthly mean (Hathaway, 2015) of the international

10   sunspot number (Clette *et al*., 2014; Clette and Lefèvre, 2016; see Figure 4) as well as

11   sunspot positions in Derfflinger's observations (Hayakawa *et al*., 2020). This was also

12   the case with frequency of reported mid-latitude aurorae in the European sector, on which

13   basis John Dalton first noted the existence of this secular minimum and after whom it was

14   subsequently named[2] (Dalton, 1834; Silverman, 1992). In fact, it is shown that auroral

15   visibility generally moved poleward, both when compiling the existing auroral reports in

16   the European sector, as well as those from Islands in the North-Eastern Atlantic Ocean

17   (Lockwood and Barnard, 2015; Vazquez *et al*., 2016).

18

19   Similar trends are found in centennial-scale reconstructions of solar activity based on a

20   number of diverse sources. Cosmogenic isotopes, such as ^{14}C and ^{10}Be, can be used to

21   estimate the time history of galactic cosmic ray (GCR) intensity reaching Earth, and thus

22   the ability of the solar magnetic field to deflect GCRs (*e.g*., Roth and Joos, 2013). This

23   shielding ability is quantified by the heliospheric modulation potential (HMP). The

24   shielding is actually caused by scattering of the GCRs by irregularities in the heliospheric

25   field, but their net effect is well quantified by the   open solar flux (OSF),   the total solar

26   magnetic flux that leaves to top of the solar atmosphere and fills the heliosphere and so

27   acts as a barrier to GCRs. Due to the multi-decadal time constants involved in the

28   terrestrial carbon cycle, reconstructions of solar activity based on the abundance of the

29   ^{14}C cosmogenic isotope, ptoduced by GCRs in Earths atmosphere and stored in terrestrial

30   reservoirs (like tree trunks) cannot resolve individual solar cycles, only secular trends

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[2] It is Sam M. Silverman who suggested this term during his discussion with Jack Eddy
and George Siscoe (private communication with S. M. Silverman in 2020).

1   (*e.g.*, the orange dashed line in the middle panel of Figure 4 which shows the estimate

2   from Roth and Joos, 2013). The faster deposition time of the ^{10}Be cosmogenic isotope,

3   and the fact that is is not subsequently exchanged between differen reservoirs, means that

4   solar activity can potentially be resolved at annual timescales. However, a number of

5   caveats apply in the interpretation of these data. The signal-to-noise in the ^{10}Be records,

6   coupled with the complexity of converting ^{10}Be concentration into a measure solar

7   magnetism means that at annual resolution the reconstructions contain uncertainties of

8   the order ± 2 years in timing and around 25% in magnitude (Owens *et al*., 2016b). The

9   red line in Figure 4 shows the HMP estimate from Muscheler *et al.* (2016), while the

10   purple line shows the B (the near-Earth heliospheric magnetic field intensity, closely

11   related to the OSF, see Figure 10 of Lockwood *et al.*, 2014) estimate from McCracken

12   and Beer (2015), filtered in the same way as (Owens *et al*., 2016b). While the same long-

13   term trend is present in both estimates of solar activity, there is less agreement about the

14   timing and magnitude of individual cycles.

15

16   OSF and near-Earth heliospheric field, B, can also be estimated from sunspot records, by

17   using assuming sunspots represent the source of new OSF and that OSF can be treated as

18   a continuity equation (Solanki *et al*, 2000). This method gives very good agreement with

19   geomagnetic reconstructions over the interval 1845-2013 (Owens *et al*., 2016a). Of

20   course, there may be long-term drifts in the calibration of the sunspot record before this

21   period (from changes in observing capability, intercalibration of different observers, *etc*.;

22   see Clette and Lefèvre, 2016; Muscheler *et al*., 2016), which makes the independent

23   estimates of cycle amplitude from ^{14}C and ^{10}Be very useful. However, the timing of

24   sunspot cycles, and hence features in the subsequent OSF reconstruction, is likely to be

25   accurate to within a year.

26

27   Figure 4 shows that the open solar flux (OSF) from the model constrained by the sunspot

28   number did not peak until mid 1806, when this eclipse took place. Further information

29   about the expected structure of the corona and solar wind can be estimated by assuming

30   new OSF is produced in the streamer belt, resulting in slow wind, which then gradually

31   transitions into coronal hole flux, resulting in fast solar wind (Lockwood and Owens,

32   2014). The time constant for this transition is a free parameter which was determined by

33   comparison with 40 years of photospheric magnetic field observations and models (see

1   Owens *et al*., 2017 for more detail). The resulting solar wind structure as a function of

2   latitude and time is shown in Figure 4. On this basis, the eclipse occurrence in mid 1806

3   occurs during an interval with slow wind at most latitudes (embedded withi which will

4   be extensions of any small remnant of the polar coronal hole and/or isolated coronal holes

5   at all latitudes), suggesting streamers should extend to most latitudes. This is broadly

6   consistent with the eclipse images (Figure 3), which showed streamers all around the

7   eclipsed Sun. As such, these two eclipse drawings in 1806 June confirm the validity of

8   the existing models of Owens *et al*. (2017) within the DM in terms of their reconstructions

9   of OSF phase and solar-wind speed as a function of latitude and time.

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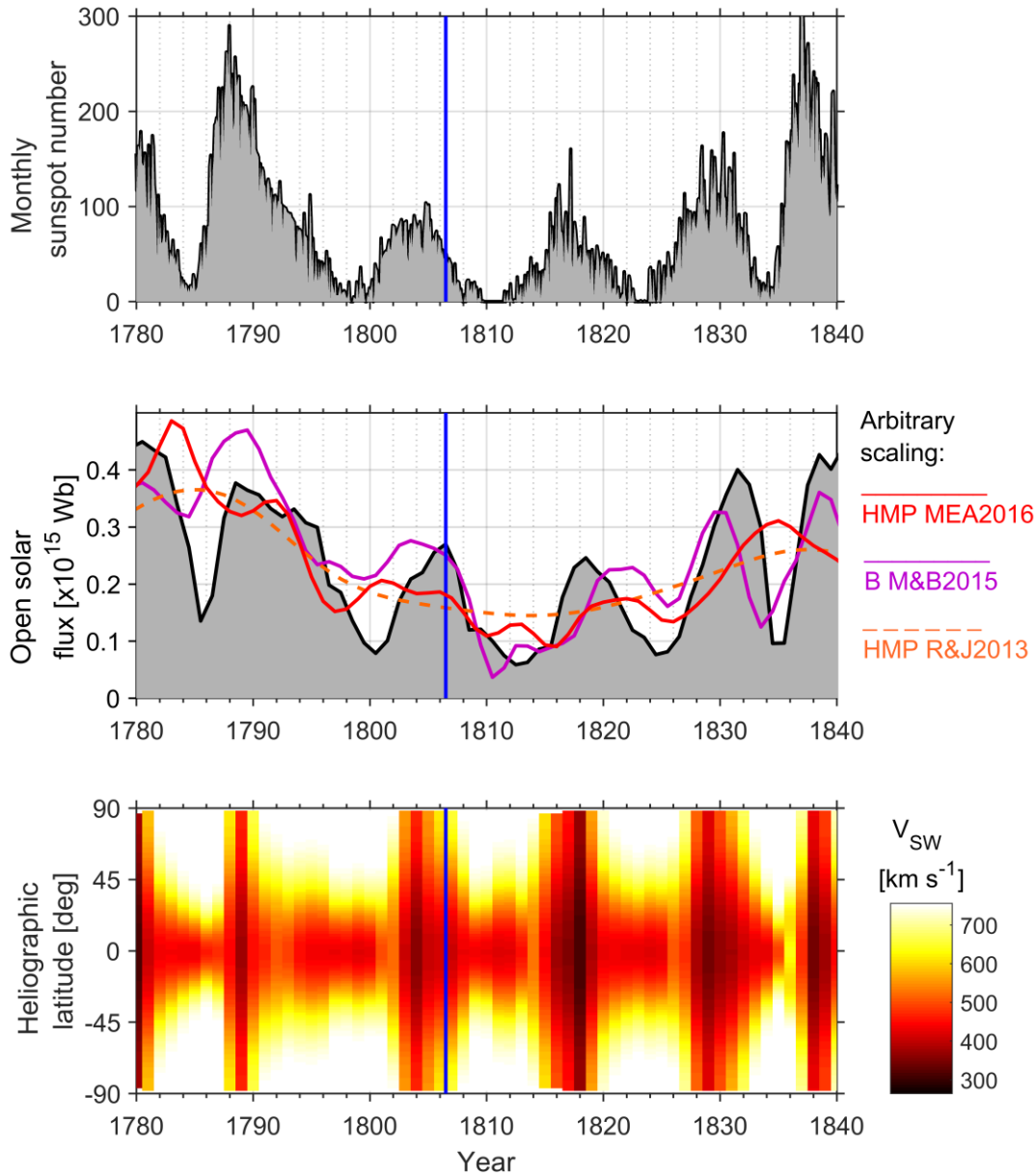
1

2   Figure 4: A summary of observed and modelled solar properties through the Dalton

3   minimum. The 1806 eclipse is shown as the blue vertical line. Top: Monthly sunspot

4   number (Clette and Lefèvre, 2016). Middle: The reconstructed open solar flux using the

5   observed sunspot number in black (Owens *et al*., 2017). The coloured lines show

6   estimates of solar activity, scaled for plotting purposes: Purple: HMF B from [10]Be

7   (McCracken and Beer, 2015; Owens *et al*., 2016b), red: heliospheric modulation potential

8   from [10]Be (Muscheler *et al*., 2016) and orange: heliospheric modulation potential from

1   ^{14}C (Joos and Roth, 2013). Bottom: The reconstructed solar wind speed as a function of

2   heliographic latitude and time (Owens *et al*., 2017).

3

4   **4. Conclusion**

5   In this article, we have examined the total eclipse drawings on 1806 June 16 and visually

6   confirmed the activity phase of the solar magnetic field in the midst of the DM. Both of

7   de Ferrer's and Ames's eclipse drawings showed corona with significant rays and

8   streamers. On the basis of de Ferrer's report, we computed the extent of the brighter and

9   the outer rays from the solar disk as $\geq 11.88\ R_\odot$, and $\approx 0.44\ R_\odot$, respectively. De Ferrer's

10   report also implies presence of prominences or solar spicules. These details confirm the

11   presence of the solar and heliospheric magnetic fields in the midst of the DM.

12

13   This marks a significant difference from the coronal structure during the MM, when

14   streamers were apparently missing or at least not bright enough to be visible and the

15   corona was recorded without significant structure. This contrast visually shows

16   significant difference of the DM with the MM in terms of their background state of the

17   solar dynamo, and robustly supports the existing discussions on the difference of the DM

18   and MM on the basis of their sunspot positions and amplitude and duration of their solar

19   cycles (Usoskin *et al*., 2015; Hayakawa *et al*., 2020). This comparisons disprove

20   postulates that the Maunder minimum was no more than an extended version of the

21   Dalton minimum such that both are similar minima of the quasi-regular Gleissberg cycle

22   (Zolotova and Ponyavin, 2015): the same conclusion was reached by Usoskin *et al.*

23   (2015) looking at a variety of other historic and paleo- datasets

24

25   Moreover, comparison these eclipse drawings is broadly consistent with the modelled

26   reconstruction on the cycle phase of OSF and on that on the solar wind speed as a function

27   of latitude and time. The OSF peaked around this eclipse and the slow solar wind

28   extended to most latitudes, suggesting streamers should also extend to most latitudes.

29   This coincidence confirms the validity of the existing model of Owens *et al*. (2017) even

30   in the midst of the DM.

31

32   **Acknowledgement**

33   We thank Ken'ichi Fujimori for his irreplaceable eclipse drawings in 1991 and 2009,

11

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