

Evolution of the Sunspot Number and Solar Wind B Time Series

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Abstract The past two decades have witnessed significant changes in our knowledge of long-term solar and solar wind activity. The sunspot number time series (1700-present) developed by Rudolf Wolf during the second half of the 19th century was revised and extended by the group sunspot number series (1610–1995) of Hoyt and Schatten during the 1990s. The group sunspot number is significantly lower than the Wolf series before ~1885. An effort from 2011–2015 to understand and remove differences between these two series via a series of workshops had the unintended consequence of prompting several alternative constructions of the sunspot number. Thus it has been necessary to expand and extend the sunspot number reconciliation process. On the solar wind side, after a decade of controversy, an ISSI International Team used geomagnetic and sunspot data to obtain a high-confidence time series of the solar wind magnetic field strength (B) from 1750-present that can be compared with two independent long-term ($> \sim 600$ year) series of annual B -values based on cosmogenic nuclides. In this paper, we trace the twists and turns leading to our current understanding of long-term solar and solar wind activity.

Keywords Sunspot number · solar wind magnetic field strength

1 Introduction

Schwabe's discovery of the "decennial" sunspot cycle based on his 1826–1843 observations (Schwabe 1844) led Wolf to compile sunspot observations for earlier years and thus extend the 11-yr solar cycle back to 1700. More recently, the impulse to extend solar and

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solar-terrestrial time series back in time, or to re-examine existing long-term series, has been manifest in attempts to determine solar wind B prior to the space age and to recalibrate the sunspot number. Both efforts involve considerable uncertainty. For the sunspot number, the primary challenge is to normalize differences in telescopes, visual acuity, observing conditions, and reporting practices between modern sunspot counters and those from earlier epochs. The challenge for solar wind reconstruction is to deduce values of solar wind parameters from indirect observations, viz., sunspot number, geomagnetic variability, and concentrations of cosmogenic nuclides in tree rings (^{14}C) and polar ice cores (^{10}Be). Research on long-term reconstructions of both the sunspot number and solar wind B was spurred by the Lockwood et al. (1999) report of a doubling of the Sun's coronal magnetic field during the 20th century. This paper led to a prolonged contentious debate on long-term solar wind B that was recently largely resolved (Owens et al. 2016a, 2016b) while, at the same time, an equally animated discussion sprang up surrounding the sunspot number time series.

In this paper, we trace the evolution of research on the sunspot number (Sect. 2) and long-term solar wind B (Sect. 3), including recent developments for the Maunder Minimum (Sect. 4). Section 5 contains a summary and a list of lessons learned.

2 Sunspot Number

2.1 Schwabe and Wolf

Sunspots were first observed telescopically in 1610 and 1611 by Galileo and others but it is fair to say that little progress was made in their understanding before Schwabe's (1844) report of the sunspot cycle. Within the following 20 years, Schwabe's discovery triggered several key advances: Earth's magnetic variability was found to track the 11-yr solar cycle (Sabine 1852; Wolf 1852a, 1852b; Gautier 1852); Carrington discovered the latitude variation of sunspots over the cycle (1858) and used sunspots to deduce the Sun's differential rotation (1859a, 1863); and the first solar flare and first confirmed solar-terrestrial event were recorded (Carrington 1859b; Hodgson 1859; Stewart 1861; see Bartels 1937). Prior to Schwabe's discovery, the prevailing view of sunspots among astronomers was that voiced by Delambre (1814; see Clerke 1902), the Director of the Paris Observatory, "It is true that the sunspots are more puzzling than really useful."

With von Humboldt's help (Hufbauer 1991), Schwabe changed this perception and set Swiss astronomer Rudolf Wolf on the scientific direction that he would take until his death in 1893. Wolf's definition of the sunspot number (1851, 1856),

$$\text{WSN} = k(10 \times N_g + N_s) \quad (1)$$

where WSN = Wolf sunspot number for a given day,¹ k = normalization factor for a secondary observer relative to the primary Zürich observer, N_g = Number of sunspot groups, N_s = Number of sunspots. Wolf intended his relative sunspot number to be an indicator of the total spotted area of the Sun. In the 1856 article, he wrote, "I was relying on the fact that the level of spottedness must be given primarily by the number of groups, but also by the number of spots as a reflection of the size of a group"... [I] "selected the number 10 that

¹The Wolf number is also referred to as the Zürich number because of the long period during which it was made in Switzerland, and, more recently, as the international sunspot number following the transfer of the curatorship to the Royal Observatory of Belgium (ROB) in 1981 (Clette et al. 2007; Stenflo 2016).

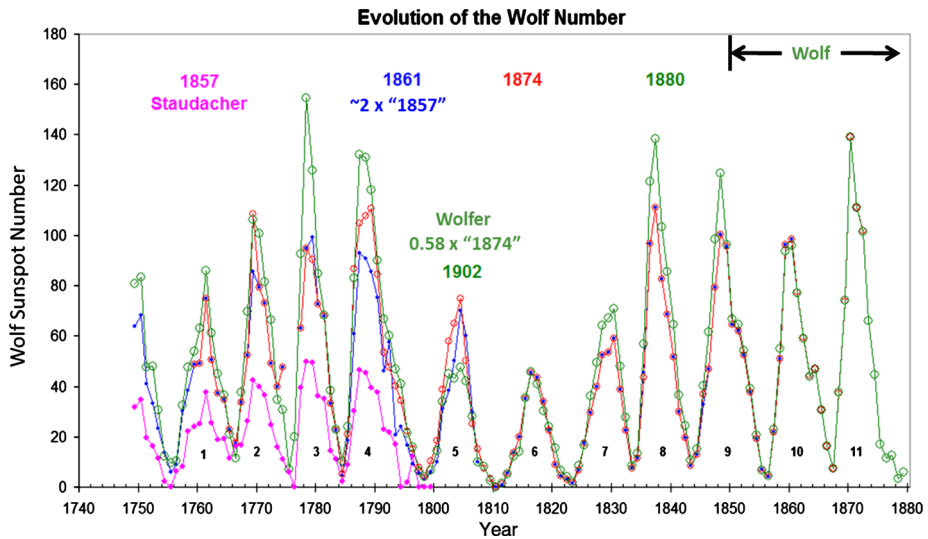


Fig. 1 Evolution of Wolf's time series, with revisions made (primarily to the pre-1848 record) by Wolf in 1861, 1874, and 1880, and by Wolf for cycle 5 in 1902 (adapted from Svalgaard 2010)

seemed to fit a large number of cases and also was more convenient than other values near it [for ease of calculation]... "I had preferred that my relative number would have been proportional to the actual area of the spots, but that would have necessitated too much work with data that I most often didn't have". In practice, it turned out that on average a group has approximately 10 spots, e.g., see Fig. 60 in Clette et al. (2014), so the WSN gives approximately equal weight to N_g and N_s . Over time, Wolf realized that the historical records of sunspot counts he acquired, predominantly from Europe, needed to be scaled up to be commensurate with his own series of observations initiated in late 1848. Thus in 1861, 1874, and 1880, he made (almost exclusively) upward adjustments to the pre-1848 series with only minor adjustments (in 1880) for years after 1848 (Fig. 1, from Svalgaard 2010). It appears that at least some of these adjustments were made with reference to the daily variation of geomagnetic activity (Loomis 1873; Hoyt and Schatten 1998a, 1998b; Cliver et al. 2015). The last adjustment to the Wolf series, a downward revision to cycle 5 (1798–1809) was made by Wolf's successor early in the 20th century (Wolf 1902).

2.2 The Maunder Minimum

The next key development regarding the sunspot number time series was Eddy's (1976) rediscovery of the prolonged sunspot drought during the second half of the 17th century, which he termed the Maunder Minimum (MM). Wolf had been stymied in his effort to extend the sunspot number time series back in time by the relative absence of reported sunspots before 1700. Subsequently Spörer (1887, 1889) and Maunder (1890, 1894, 1922) called attention to this episode of apparently anomalous behavior, but few astronomers paid attention until Eddy's landmark paper. Eddy bolstered the case for an interval of unusually low sunspot activity from 1645–1715 with cosmogenic nuclide data (^{14}C) and chose the alliterative name "Maunder Minimum" (vs. Spörer Minimum; see the transcribed interview of Jack Eddy by Spencer Weart at https://history.aip.org/climate/eddy_int.htm) to describe it. In addition, he extended Wolf's annual time series of sunspot numbers back to 1610,

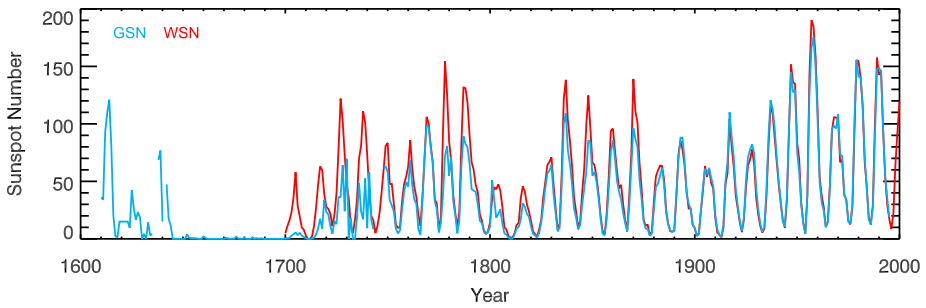


Fig. 2 Comparison of the Wolf sunspot number (WSN) with the Hoyt and Schatten (1998a, 1998b) group sunspot number (GSN), 1610–1995 (adapted from Clette et al. 2015)

with many years during the 1645–1700 core of the Maunder Minimum (Vaquero and Trigo 2015) having sunspot numbers of zero. The highest average sunspot number Eddy calculated for any year during this ~ 50 year period was 11 (in 1684) vs. annual values ranging from ~ 150 – 190 at the maxima of cycles 18, 19, 21, and 22, spanning the ~ 1945 – 1995 interval. Eddy’s paper and supporting work, notably that of Ribes and Nesme-Ribes (1993), Beer et al. (1998), and Berggren et al. (2009) established the Maunder Minimum, the persistence of the 11-yr cycle during the MM, and long-term variability in the envelope of 11-yr solar maxima as basic tenets of solar physics.

2.3 The Group Sunspot Number

In his landmark paper, Eddy (1976) commented that, “Past counts of sunspot numbers are readily available from the year 1700 [...], and workers in solar and terrestrial studies often use the record as though it were of uniform quality. In fact, it is not. Thus it is advisable from time to time, to review the origin and pedigree of past sunspot numbers, and to recognize the uncertainty in much of the early record.”

In 1994, Hoyt et al. took up Eddy’s challenge in *Geophysical Research Letters*, titling their paper: “The one hundredth year of Rudolf Wolf’s death: Do we have the correct reconstruction of solar activity?” Their answer, given in Hoyt and Schatten (1998a, 1998b), was in the negative. Their revised sunspot number time series, based solely on the daily number of sunspot groups (N_g in Eq. (1)), was significantly lower than the Wolf series before 1882 (see blue line in Fig. 2). The new Hoyt and Schatten “group” sunspot number (GSN) was defined as

$$\text{GSN} = 12.08k' \times N_g \quad (2)$$

where the factor of 12.08 scaled group counts to the Wolf number and k' was the normalization factor used to scale secondary observers to the primary Royal Greenwich Observatory (RGO; Willis et al. 2013a, 2013b, 2016a, 2016b; Erwin et al. 2013) reference series (1874–1976). In deriving the GSN, Hoyt and Schatten (1998a, 1998b) greatly expanded the data base that Wolf and his successors at Zürich had compiled, achieving, e.g., an increase of 80% in the number of individual daily observations of sunspot groups for years before 1874. Moreover, they digitized the entire data base, making it accessible to all through the World Data Centers (<https://www.ngdc.noaa.gov/stp/space-weather/solar-data/solar-indices/sunspot-numbers/group/>). The new GSN time series

was used to support the notion that the recent period of intense solar activity from ~ 1945 –1995 was the strongest in several thousand years (Solanki et al. 2004; Usoskin et al. 2007; Usoskin 2017) and represented a Modern Grand Maximum, a counterpoint to the Maunder Minimum and an earlier Grand Minimum (Spörer, 1390–1550: Usoskin 2017) identified in the ^{14}C record by Eddy (1976).

2.4 The Sunspot Number Workshops

For more than a decade following the publication of the Hoyt and Schatten (1998a, 1998b) GSN, the solar community lived with two disparate solar activity time series, both widely used, with no consensus as to which was more correct. The choice of which sunspot number to use became a free parameter in solar and solar-terrestrial physics. Some argued that because the WSN and GSN had different prescriptions, it should not be surprising that their time series differed. This prompted the rejoinder: Why should series which agree reasonably well after ~ 1885 (see Fig. 2) part company for earlier times? Clearly further scrutiny was in order. In 2011, Frédéric Clette, who had shortly before become the Director of the World Data Center responsible for the production of the sunspot number, initiated an effort to address this unacceptable situation. A series of sunspot number workshops from 2011–2014 (Cliver et al. 2013a, 2015; Clette et al. 2014), co-organized by Clette, Ed Cliver of the US Air Force Research Laboratory, and Leif Svalgaard of Stanford University, examined the two discordant time series in Fig. 2 in an attempt to understand the cause of the differences between them and achieve a reconciliation, if possible.

In the course of the workshops, discontinuities were discovered in both the WSN and GSN time series. The Wolf series exhibited four inhomogeneities: (1) ca. 1850, at the join of the Schwabe and Wolf series (Leussu et al. 2013); (2) ~ 1865 , change of observers/telescopes at Zürich (Clette and Lefèvre 2016); (3) after 1946, reflecting the change in directorship at Zürich from Brunner to Waldmeier near that time (Lockwood et al. 2014c; Clette et al. 2014; Clette and Lefèvre 2016; Lockwood et al. 2016a, 2016d, 2016e; Friedli 2016; Svalgaard et al. 2017); and (4) after 1980, resulting from the transfer of production of the sunspot number from Zürich to Brussels in that year (Clette et al. 2014, 2016a). The third of these discontinuities, uncovered by Svalgaard (2010, 2012), was caused by Waldmeier's decision to break from previous procedure by weighting individual sunspot numbers according to their size. Thus the standard definition of the WSN given in Eq. (1) and all solar physics textbooks or monographs (e.g., Zirin 1988; Foukal 2004) was not followed after 1946.² Equally surprising, the post-1980 inhomogeneity was due to a complex drift in the group counts of the Locarno station, the reference observer for the international sunspot number, that was not apparent in the group count time series of other long-term observers during this period. The GSN was found to be too low before ~ 1885 because of an inhomogeneity in the early years of the group count time series from RGO that Hoyt and Schatten (1998a, 1998b) used as a reference observer (Clette et al. 2014; Cliver and Ling 2016; Cliver 2017; cf., Willis et al. 2016a, 2016b; Lockwood et al. 2016e) and the flawed and somewhat opaque procedure Hoyt and Schatten used to normalize observers who did not overlap with RGO (Cliver and Ling 2016; Cliver 2017).

The end products of the sunspot number workshops, viz., a revised WSN series and an independently-derived GSN time series, are shown in Fig. 3(a). The modified WSN series,

²This practice may have been implemented on a trial basis before Waldmeier (Friedli 2016; Svalgaard et al. 2017) but the effect is not apparent until after 1946. The weighting was stopped with the publication of the new WSN (Clette et al. 2015). Thus the formula in Eq. (1) is correct again.

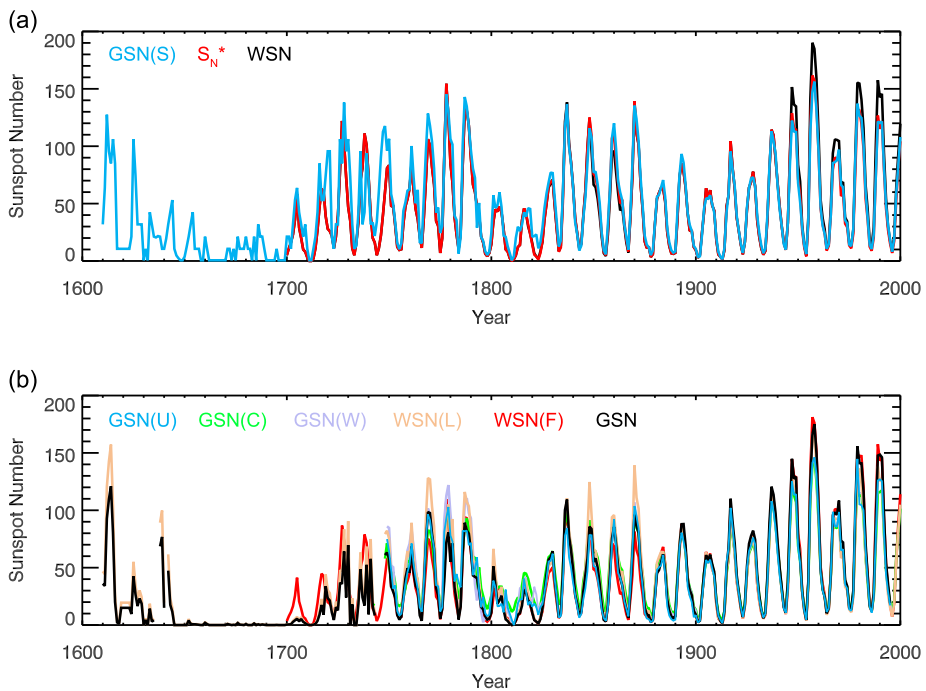


Fig. 3 (a) Comparison of the two new time series produced during the sunspot number workshops— S_N^* ($= 0.6 \times S_N$, where S_N is the corrected WSN series of Clette and Lefèvre (2016), and GSN(S), the newly constructed GSN series of Svalgaard and Schatten (2016)—plotted along with the original WSN series that they resemble. (b) Sunspot number time series produced independently of the sunspot number workshops—GSN(U) Usoskin et al. (2016), GSN(C) Chatzistergos et al. (2017), GSN(W) Willamo et al. (2017), WSN(L) Lockwood et al. (2014c, 2014d; revised in Lockwood et al. 2016d, 2016e), WSN(F) Friedli (2016)—plotted with the Hoyt and Schatten (1998a, 1998b) GSN time series they resemble. All series in (a) and (b) are scaled to WSN over the 1916–1946 interval

designated S_N (version 2.0; Clette and Lefèvre 2016 (red line)), employed corrections for the inhomogeneities 1–4 noted above. The independently-derived GSN-type series was based on a “backbone” approach that used multiple reference observers in order to minimize the uncertainty that results from the daisy-chaining needed to link distant secondary observers to a single primary observer (Svalgaard and Schatten 2016 (light-blue line)). The two new series in Fig. 3(a) track each other reasonably well and adhere more closely to the original WSN (black line) than to the Hoyt and Schatten GSN. The reconciliation sought by the sunspot number workshops was achieved but it proved to be short-lived.

2.5 Unintended Consequences and the Path Forward

The new S_N series was published on the website of the World Data Center for the Solar Index and Long-term Solar Observations (WDC-SILSO; <http://sidc.oma.be/silso/>) at ROB (Clette et al. 2015) and a Topical Issue in *Solar Physics* (Clette et al. 2016b) called for papers to both document and comment on the new time series. In a classic case of unintended consequences, the results exceeded expectations of the sunspot number workshop organizers. Criticism of the new GSN of Svalgaard and Schatten (e.g., Lockwood et al. 2016a, 2016b, 2016c, 2016d) was accompanied by the introduction of alternative GSN

(Usoskin et al. 2016) and Wolf-type (i.e., based on the formula in Eq. (1)) time series (Friedli 2016) which more closely resembled the Hoyt and Schatten GSN than the original WSN. Earlier, Lockwood et al. (2014c, 2014d; revised in Lockwood et al. 2016d, 2016e) had introduced a new Wolf-type series that was somewhat intermediate between the two new time series that resulted from the sunspot number workshops (Clette and Lefèvre 2016; Svalgaard and Schatten 2016) and those of Usoskin et al. (2016) and Friedli (2016). Detailed comparisons/critiques of these various new sunspot number series are given in Lockwood et al. (2016e) and Cliver (2016). Recently, Chatzistergos et al. (2017) introduced another GSN time series that is similar to that of Usoskin et al. (2016) which itself has been updated by Willamo et al. (2017). Figure 3(b) shows the time series of Usoskin et al. (2016; light blue trace), Chatzistergos et al. (2017; green), Willamo et al. (2017; light purple), Lockwood et al. (2016d, 2016e; light orange), and Friedli (2016; red), along with that of the original Hoyt and Schatten (1998a, 1998b; black) GSN.

Comparison of Fig. 3(a) and Fig. 3(b) indicate that the circumstance of the existence of two discordant time series (WSN and GSN) for long-term solar activity that motivated the sunspot number workshops has been exacerbated. Now, instead of two disparate series, the solar community has, to first order, two *classes* of series, with both WSN- and GSN-type series in each class. Moreover, the various new time series differ widely in their choices of standard or reference observers (e.g., RGO vs. Wolfer) and the techniques used to scale secondary observers to the standard observer (e.g., linear regression vs. a non-linear non-parametric probability distribution function). A key schism among the new proposed series involved the central problem of comparing of secondary observers with non-overlapping primary or reference observers. In the traditional daisy-chaining approach of Hoyt and Schatten (1998a, 1998b), secondary observer C who does not overlap with primary observer A is scaled to A through observer B who does; then D is linked to C, and so forth. In the backbone method (Svalgaard 2013; Clette et al. 2014; Svalgaard and Schatten 2016; Chatzistergos et al. 2017), the error propagation/accumulation inherent in daisy-chaining is reduced by designating several primary or backbone observers, scaling all overlapping secondary observers to them, and then linking the backbones together. In effect, the number of links between non-overlapping observers is reduced in such a scheme, providing fewer opportunities for error to creep in. Alternatively, the innovative active day fraction method proposed by Usoskin et al. (2016; and refined by Willamo et al. 2017) eliminates daisy-chaining altogether by scaling all secondary observers (regardless of overlap or non-overlap) directly to RGO by a comparison of the fraction of days per month the secondary observer reported (non-zero) spot groups (a measure of observer quality) with the corresponding fraction for RGO. The Usoskin et al. (2016), Willamo et al. (2017), and Chatzistergos et al. (2017) time series employ advanced non-linear techniques to scale secondary observers to primary observers vs. the combination of linear and non-linear regression used by Svalgaard and Schatten (2016) and criticized in, e.g., Lockwood et al. (2016c; cf., Svalgaard and Schatten 2017).

The situation facing the solar community in 2016 was thus scientifically complicated and, on a human level, becoming increasingly contentious. The danger was that the proliferation of new disparate series, if left unaddressed in a systematic fashion, would render the sunspot number meaningless as a measure of solar activity. How to proceed?

Matters came to a head at the Space Climate 6 Symposium in Levi, Finland in April 2016. Following a lively scientific session devoted to the sunspot number, developers of the new sunspot series held an informal meeting and agreed to work together to examine the causes of their differences and to reconcile them, in so far as possible—in other words, to continue, on a broader scale, the effort that was begun under the sunspot number workshops. The end

Fig. 4 Pierre-Nöel Mayaud (1923–2006), creator of the geomagnetic *aa* time series. Mayaud was a Jesuit who wrote the “bible” (Mayaud 1980) on geomagnetic indices. After he left geophysics, he became an authority on the interaction between the Catholic church and Galileo



goal is the creation of community vetted and accepted versions of both the GSN and WSN time series (with stated uncertainties, e.g., Dudok de Wit et al. 2016) and the establishment of a procedure for publication of further revisions as warranted. This work is underway, first involving small teams that are examining each series separately, to be followed by larger group meetings that will identify/implement best practices for series construction, with a targeted release date of 2019 for the new versions of the two series.

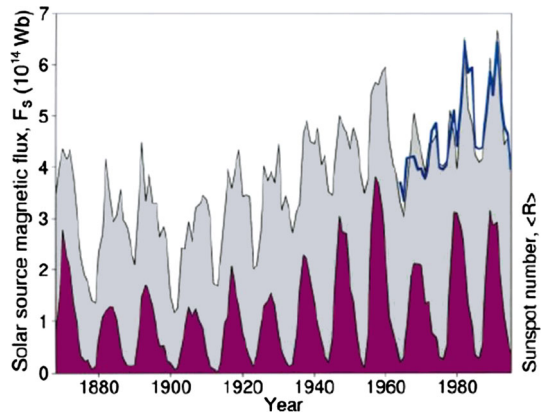
3 Solar Wind *B* Time Series

Fortunately, solar scientists have recent experience in dealing with a situation similar to that which has arisen for the sunspot number. The long-term time series in question previously was that for the solar wind magnetic field strength (*B*). We will spend some time recounting the evolution of that time series. It contains the various elements—conflicting findings, error, insight, miscommunications, confusion, emerging consensus and resolution—characteristic of scientific debate. The positive outcome of the work on solar wind *B* underwrites the present effort to reconcile the various sunspot number time series. For recent independent accounts of the evolution of thinking on long-term solar wind activity, see Usoskin (2017) and Lockwood et al. (2017).

3.1 Doubling of the Sun’s Open Magnetic Flux During the 20th Century

Because geomagnetic activity is driven by the solar wind, solar wind parameters—first available directly from space observations in the early 1960s (Neugebauer and Snyder 1962; Snyder et al. 1963)—can be extracted from geomagnetic observations for earlier years. In 1972, P.-N. Mayaud, pictured in Fig. 4, published a new long-term (1868–1967) geomagnetic index, termed *aa* (Mayaud 1972), based on sequences of geomagnetic stations in the UK and Australia, that significantly extended the objective, easily accessible, record of geomagnetic activity, more than doubling the length of *ap* series (available from 1932) at the time. Following Russell (1975), Feynman and Crooker (1978) used the empirically-derived dependence of *aa* ($\sim V^2 B_S$; where B_S is the magnitude of the southward-pointing component of *B* and *V* is the solar wind speed) on solar wind parameters to constrain the range of B_S to 0.65–1.75 nT and *V* to 240–400 km s⁻¹ for the solar minimum year of 1901, at the depth of a minimum of the \sim 100-yr Gleissberg cycle. Because *aa* depends on both *B* and *V*, a second relationship involving either *B* and/or *V* is needed for further specificity.

Fig. 5 Top: Modeled open solar flux (gray-shaded plot) from 1868–1996 with observed values (dark blue line). Bottom: sunspot number. (From Lockwood et al. 1999.)



Approximately two decades after Feynman and Crooker’s pioneering paper, Lockwood et al. (1999) used Sargent’s (1986) recurrence index, which is a measure of the 27-day repeatability of geomagnetic activity, as a proxy for solar wind speed and thus were able to deduce from the aa index an annual time series for the open solar open flux (OSF), based on the radial component B_r of the solar wind magnetic field, from 1868 to the present.³ Lockwood et al. (1999) found a doubling (increase by 131% from 1901 to 1992) of the coronal magnetic field over the 20th century (see Fig. 5). In the same paper, these authors reported a 41% increase in OSF between the solar minima in 1964 and 1996. In a key development, Solanki et al. (2000) introduced a model for the long-term time evolution of the open solar flux with which they were able to reproduce the doubling of the OSF during the 20th century reported by Lockwood et al. (1999). However, Arge et al. (2002), using a potential field source surface model and solar magnetogram data from three different observatories found no evidence for an increase in the open flux between the minima of 1976 and 1996. They wrote, “Thus the Lockwood et al. claim that open solar flux has increased by 41% from 1964 to 1995 would require that the entire increase must have occurred over the twelve-year period between 1964 to 1976, which does not seem credible.” At the same time, Wang and Sheeley (2002) obtained a record of the OSF similar to that of Arge et al. (2002) but noted that the fact that the open flux was higher on average during strong cycles 21 and 22 than in weaker cycles 20 and 23 tended to support the finding of Lockwood et al. (1999) of a secular increase in the open flux over the last century, given the overall increase in sunspot activity since 1900.

Although both Svalgaard (1977) and Cliver and Ling (2002) noted evidence in the geomagnetic record that was consistent with a doubling of the open solar flux during the 20th century, they disputed the Lockwood et al. (1999) result in a paper submitted to *Nature* in 2003 entitled “No Doubling of the Sun’s Coronal Magnetic Field During the Last 100 years”. The “no doubling” paper was based largely on a newly-derived inter-hourly variability (IHV) long-term geomagnetic index (Svalgaard et al. 2004; first presented at CoSpaR 2002). For a single station, IHV is defined to be the sum of the [unsigned] differences between each hourly-averaged value and the next of the horizontal component of the geomagnetic field for the 6 h around local midnight, divided by 6. A key attribute

³Lockwood et al. (1999) also employed the “Ulysses result” (Balogh et al. 1995; Smith and Balogh 1995; Lockwood et al. 2004; Lockwood and Owens 2009) that B_r (normalized to 1 AU) is independent of latitude when averaged over a rotation cycle or more, thus permitting the determination of OSF from a point measurement of B_r .

of the *IHV* index is its objectivity and ease of construction from early geomagnetic data which often is readily available only in the form of hourly values (Svalgaard et al. 2004; Svalgaard and Cliver 2005). Comparison of the *IHV* index with *aa* indicated that the *aa* index was significantly too low (by $\sim 5\text{--}10$ nT) for the early years of the 20th century and was thus responsible for the inferred doubling of the coronal magnetic field reported by Lockwood et al. (1999). Fortunately, the “no doubling” paper was rejected for publication because the referees were not convinced that the *aa* index rather than the new *IHV* index was the principal source of the discrepancy. Subsequently, it was found that *aa* was artificially low by $\sim 2\text{--}3$ nT before 1957 (Jarvis 2005; Lockwood et al. 2006, 2009a; Svalgaard and Cliver 2007b), but that the principal cause of the difference between *IHV* and *aa* that underpinned the no doubling claim was an error in the interpretation of the raw geomagnetic data used to construct *IHV*. This error, detected by Svalgaard, was corrected in a note added in proof to the 2004 *IHV* paper which read: “*IHV* calculated for Cheltenham before 1915 should be reduced by 30% because it was based on a single reading per hour rather than on the average for an hour. This increases the variability and thus *IHV*. Values after 1915 are not affected.” This change in recording from “spot” to hourly-averaged values at individual stations, occurring for British stations in 1912 and all American stations in 1915, is a common feature in long-term geomagnetic archives (Svalgaard and Cliver 2005, Sect. 2.1; 2007b, Appendix A2; Love et al. 2010).

The early geomagnetic data contained other station-unique artefacts, e.g., the records in the World Data Centers for the long-running Eskdalemuir (ESK) station were affected by two-point averaging of observed hourly values from 1911–1931 (Martini and Mursula 2006; Svalgaard and Cliver 2007b, Appendix A4.1; Macmillan and Clarke 2011). The net effect of this “post-processing” was to inflate 20th century increases in *IHV* and *aa* indices obtained by Mursula et al. (2004) and Clilverd et al. (2005), respectively, that were based in part on ESK observations.

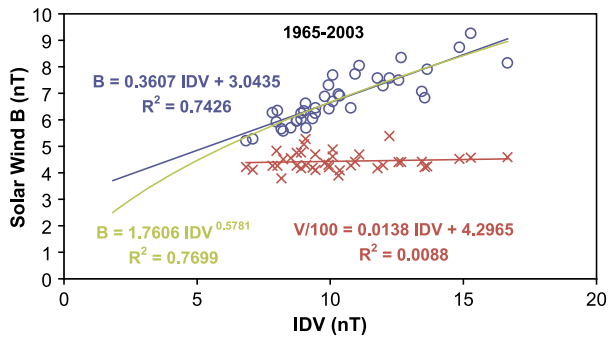
3.2 Interdiurnal Variability of Geomagnetic Activity

In his 1977 paper on geomagnetic activity and solar wind parameters, Svalgaard wrote, “It would be very desirable to infer the interplanetary magnetic field strength independently from the solar wind speed from geomagnetic data.” Twenty-six years later, in 2003, he achieved this goal with the realization that the geomagnetic *u*-index is not sensitive to the solar wind speed, but only to the IMF magnitude. The daily *u*-index (at a given station) developed by Bartels (1932), who termed it the interdiurnal variability, was the difference, regardless of sign, between successive daily means of the magnetic horizontal intensity. Svalgaard et al. (2003) retained the interdiurnal variability name but used the descriptor *IDV* to distinguish it from the *u*-index because *IDV* is based on only the single hour (taken to start 1 hour after the UT hour closest to local midnight) for consecutive days.⁴ As shown in Fig. 6, *IDV* “has the useful property that its yearly averages are highly correlated with the solar wind magnetic field strength (*B*) and are independent of solar wind speed (*V*)” (Svalgaard et al. 2003). Thus the *IDV* index yields solar wind *B* directly and, in conjunction with *IHV*, solar wind *V* from hourly data for the second half of the 19th century. Svalgaard and Cliver (2005) showed that *IDV* is highly-correlated, on average, with the negative component of the *Dst* index.

Svalgaard and Cliver (2005) used *IDV* to construct a time series for *B* from 1872–2004. Based on this time series and a proportional relationship between *Br* and *B* ($Br = 0.53B$)

⁴For *IDV*, as well as *IHV*, restriction to night time hours removes contamination by the EUV-driven regular ionospheric variation.

Fig. 6 Scatter plot showing the correlation between solar wind magnetic field strength at 1 AU (B) and the IDV geomagnetic index from 1965–2003 and the negligible dependence of IDV on solar wind speed (V) during this period (adapted from Svalgaard and Cliver 2005)



in Lockwood et al. (1999), they reported that, “solar cycle average B increased by $\sim 25\%$ from the 1900s to the 1950s and has been lower since”, consistent with a Gleissberg-type (~ 100 -yr) cycle (Gleissberg 1939; Feynman and Ruzmaikin 2011; Hathaway 2015; Le Mouél et al. 2017) during the 20th century. This paper prompted a comment by Lockwood et al. (2006; response in Svalgaard and Cliver 2006) who argued that the estimate of $\sim 25\%$ was too low and determined an increase of 38% based on the ratio of 11-yr running means in 1956 (near sunspot cycle maximum) and 1903 (near minimum) for the B values given in Table 3 of Svalgaard and Cliver (2005). Moreover, Lockwood et al. argued that for a more valid averaging interval for B of one-day vs. the one hour averages used in Lockwood et al. (1999), the proportional relationship between B and Br should be replaced by a linear relationship with an offset ($Br = 0.55B - 0.91$), implying a 54% increase in smoothed Br from 1903–1956 based on the Svalgaard and Cliver B series. Lockwood et al. (2006) questioned the method used by Svalgaard and Cliver (2005) to treat gaps in the observed solar wind data and their B vs. IDV regression analysis. Using an alternative technique for data gaps and a least median of squares regression method for a correlation between IDV and Br , Lockwood et al. (2006) obtained an 85% increase in 11-yr averaged Br from 1903 to 1956.

3.3 Stumbling in the Dark

The exchange between Lockwood et al. (2006) and Svalgaard and Cliver (2006) was accompanied by a related debate on the long-term reconstruction of solar activity based on cosmogenic radionuclides. In that field, Solanki et al. (2004), from an analysis of the GSN and the record of ^{14}C concentration in tree rings, calculated that the interval of solar activity from ~ 1940 –2000 was the strongest in the last ~ 8000 years. Following Usoskin et al. (2007), this ~ 60 -yr interval came to be called the Modern Grand Maximum (MGM). In contrast, Muscheler et al. (2005) used a ^{14}C -based reconstruction of the solar modulation parameter (empirically related to B ; e.g., Fig. 12 in Cliver et al. 2013b) and deduced high levels of this parameter during the second half of the 18th century that were comparable to those during the MGM. They noted that Bard et al. (2000) had earlier reported similar results based on ^{10}Be measurements from the South Pole. In response, Solanki et al. (2005) argued that the Muscheler et al. (2005) result was in conflict with other independent proxy time series for long-term solar activity such as that based on the ^{44}Ti cosmogenic nuclide (Bonino et al. 1995).

In short, long-term behavior of solar wind activity was a controversial topic in the middle of the last decade, with no resolution in sight. This scientific turbulence and confusion continued during 2007. From comparisons of their IDV -based B with the yearly-averaged

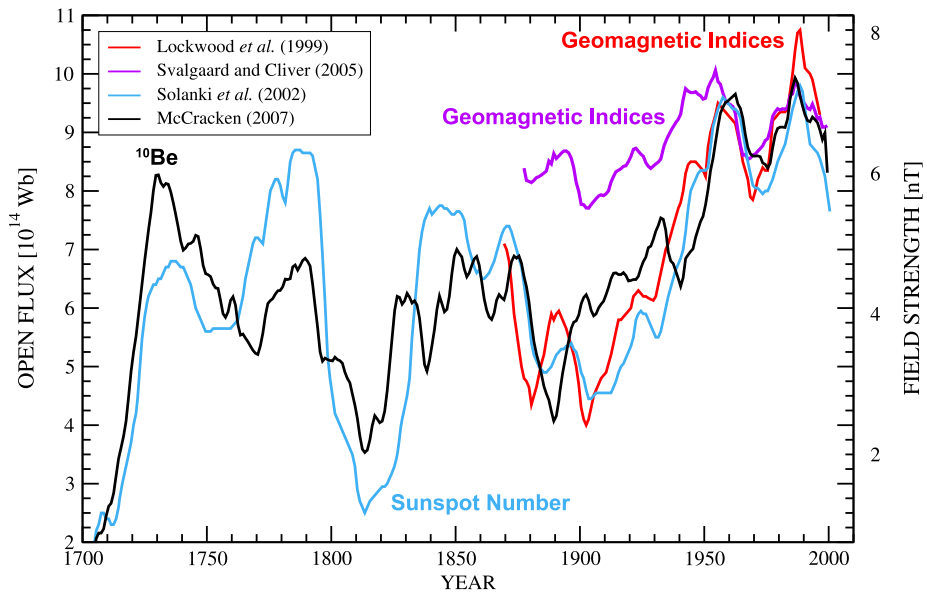


Fig. 7 Reconstructions of solar open flux (*OSF*) and solar wind *B*: *OSF* from Lockwood et al. (1999) based on geomagnetic data; *B* from Svalgaard and Cliver (2005) based on *IDV*; *OSF* from Solanki et al. (2002) based on the sunspot number; and *B* from McCracken (2007) based on ^{10}Be . All plots are 11-yr running averages. (Adapted from McCracken 2007.)

sunspot number, Svalgaard and Cliver (2007a) concluded that there was a “floor” in annual averages of solar wind *B* of 4.6 nT below which *B* would not drop. In the same month (April) that the paper was published, monthly-averaged *B* dropped below 4.6 nT and remained there for 30 of the next 32 months. Annual averages of *B* were 4.5 nT, 4.2 nT, and 3.9 nT for 2007, 2008, and 2009, respectively. In May 2007, Rouillard used a newly devised, mid-latitude range index (similar to *aa*, *ap*, and *IHV*), designated the *m*-index (for median), in conjunction with a corrected (for the pre-1957 deficit discussed in Sect. 3.1) *aa* index *aa_c*, to obtain time series of both *B* and *V*. Using a Bayesian least squares regression technique, they found an increase of 87% in the open solar flux between 11-year running means in 1903 and 1956. Their Fig. 6 indicated an anomalous spike in *V* near the 1901 minimum of cycle 14 which would lead to an under-estimate of the open flux at this time (and a corresponding over-estimate in the increase of this parameter between cycles 14 and 19). Generally, however, their series for *B* resembled that of Svalgaard and Cliver (2005). In September, however, McCracken (2007) published a long-term time series for solar wind *B* based on ^{10}Be that re-emphasized the differences between the time series of Lockwood et al. (1999) and Svalgaard and Cliver (2005). Figure 7, taken from McCracken’s paper, contains plots of 11-yr running averages of time series for: solar open flux from Lockwood et al. (1999) based on geomagnetic data, solar wind *B* from Svalgaard and Cliver (2005) based on *IDV*, solar open flux from Solanki et al. (2002) based on the sunspot number, and solar wind *B* from McCracken (2007) based on ^{10}Be . McCracken wrote that, “The agreement between curves 1 [Lockwood et al. 1999], 3 [Solanki et al. 2002], and 4 [McCracken 2007] in Fig. 7 provides confidence in the overall validity of these three independent methods.” He added, “It is important, however, that the disagreement between curve 2 [Svalgaard and Cliver 2005] and the other three be resolved.”

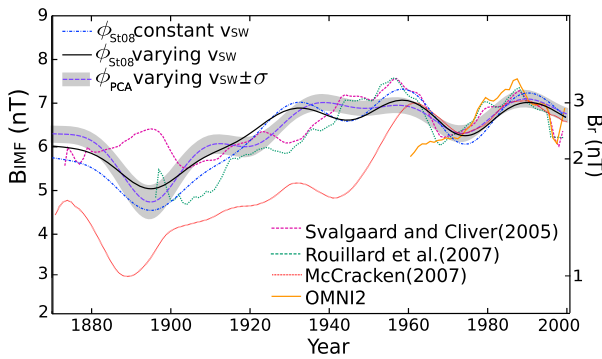


Fig. 8 Comparison of three reconstructions of solar wind B (left-hand y-axis) from Steinhilber et al. (2010; key in upper left corner) with other reconstructions and observation (lower right corner). Calculated Br is given on the right-hand y-axis. The Steinhilber et al. plots are 40-yr running means (Φ_{St08}) and 25-yr running means (Φ_{PCA}). The comparison plots (Svalgaard and Cliver 2005; Rouillard et al. 2007; McCracken 2007; OMNI2) are 11-yr running means. (From Steinhilber et al. 2010.)

3.4 Approaching Consensus

Lockwood et al. (2009a) used the aa_C index and the m -index to derive a time series for B that, other than for a few years in cycle 14 (from 1905, when the reconstruction began, to ~ 1910) was quite similar to the Svalgaard and Cliver (2005) series. In this reconstruction, they employed a correction for Br that makes allowance for the kinematic effect of longitudinal structure in solar wind flow speed (Lockwood et al. 2009b). Subsequently, a ^{10}Be -based reconstruction of B from Steinhilber et al. (2010) reproduced in Fig. 8 represented a marked departure from the McCracken (2007) time series for this parameter and agreed reasonably well with that of Svalgaard and Cliver (2005). Things were beginning to converge, at least for the post-1870 time period. Regarding the longer-term level of solar activity, Steinhilber et al. (2010) published the long-term reconstruction of B shown in Fig. 9 which indicated that the Svalgaard and Cliver (2005) floor at 4.6 nT, already violated by direct observations from 2007–2009, was also breached on numerous occasions in the past, including the Maunder (1645–1715) and Spörer (1390–1550) Grand Minima.

Svalgaard and Cliver (2010) updated their IDV -based B series and called attention to the increasing convergence of the various geomagnetic-based time series of B (see Fig. 10(a)). Lockwood and Owens (2011) concurred, reminding, however, that Lockwood et al. (1999) computed the variation of the open flux rather than B . Figure 10(b), taken from their paper, shows that a proper reconstruction of B from the OSF , taking into account the role of V (Eq. 5 in Lockwood et al. 1999), agreed more closely with subsequent reconstructions than had been indicated in Fig. 10(a). As further evidence of convergence, Cliver and Ling (2011) used the B values from Svalgaard and Cliver (2010) and IHV -based V values from Svalgaard and Cliver (2007b) to deduce an increase of 84% in the open solar flux between the sunspot minimum years of 1901 and 1954, comparable to the values obtained by Lockwood et al. (2006) and Rouillard et al. (2007) from 11-yr running means for 1903 and 1956.

3.5 ISSI International Team

Bolstered by the results shown in Fig. 8 and Fig. 10, Svalgaard, Lockwood, and Beer proposed to ISSI in 2011 that an International Team be convened to systematically examine

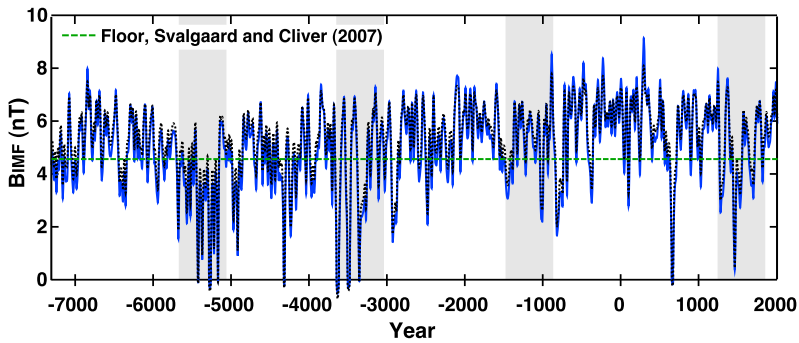


Fig. 9 Reconstruction of 40-yr running means of solar wind B for the past 9300 years. The solid-blue (dotted-black) curve assumes a constant (varying) solar wind speed. The dashed-green line shows the floor of Svalgaard and Cliver (2007a). Note the multiple excursions to $B \approx 0$ nT, including during the Spörer minimum, ca. 1500 (adapted from Steinhilber et al. 2010)

geomagnetic, solar, and cosmogenic radionuclide data to derive a consensus long-term series for solar wind B . Quoting from the proposal abstract,

After a decade of vigorous research, reasonable agreement has been achieved between IMF strength (and open flux) estimates based on geomagnetic data and the inversion of the paleo-cosmic radiation data for the last ~ 100 years. [...] The [primary] purpose of the workshop is [...] to [...] extend/substantiate the geomagnetic-based reconstruction of solar wind parameters from ~ 1840 –2010 and to resolve the remaining discrepancies among the geomagnetic-, cosmic-ray-, and sunspot-based reconstructions [...]

The principal results of the resulting ISSI team meetings are summarized here.

3.5.1 Long-Term B Series Based on the IDV Index and on the Sunspot Number

Owens et al. (2016a, 2016b) obtained three separate time series for B based on the three types of data considered (geomagnetic, sunspot, and cosmogenic radionuclides), and their correlations with directly observed solar wind B , B [OBS]. Of these three time series, the one based on geomagnetic data (1845–2013) is considered to be the “gold standard”. It is a composite of IDV-based B series from Lockwood et al. (2013a, 2013b, 2014a, 2014b; see Fig. 11(a)) and (Svalgaard 2014; Fig. 11(b)). The Svalgaard et al. series considers data from all stations at corrected geomagnetic latitudes $\lesssim 150^\circ$ for only the hour taken to start 1 hour after the UT hour closest to local midnight. The Lockwood et al. approach considers only a single chain of magnetometers but all 24 hourly-observations, similar to Bartels’ u -index. As a measure of the robustness of IDV, the results produced by both methods are very similar as can be seen in (Fig. 11(c)). Following Lockwood et al. (2013b, 2014b), the B [GEO] composite and uncertainty bands in Fig. 11(c) are based on a Monte Carlo technique that considered $\sim 17,000$ realizations of correlations of the two IDV-based series with actual observations, weighted approximately 3:2 toward the Svalgaard method. A similar approach was used to obtain a sunspot number based time series for B from 1749 to present (Fig. 12). In that case, time series for B , based on two separate methods, were constructed from B [OBS] for the space age and the sunspot number time series of Lockwood et al. (2014c, 2014d; Fig. 12(a)), Clette and Lefèvre (2016; Fig. 12(b)), Svalgaard and Schatten (2016; Fig. 12(c)), and

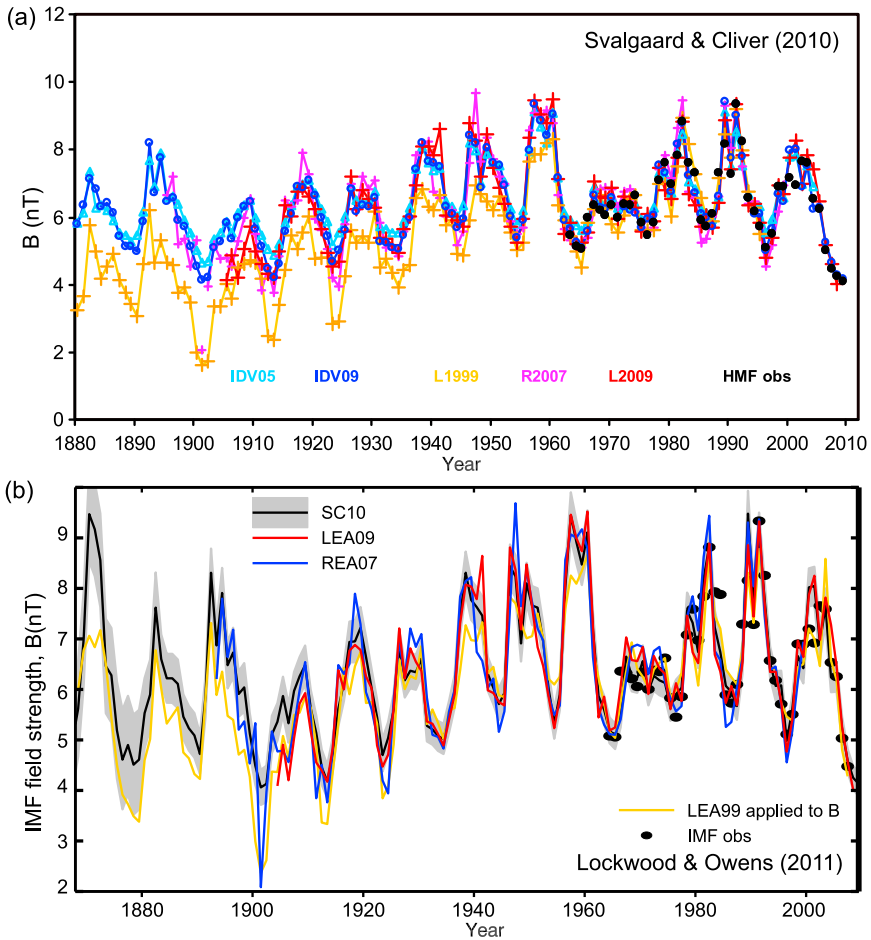


Fig. 10 (a) Figure from Svalgaard and Cliver (2010) showing emerging consensus in reconstructions of solar wind *B*. The plots of annual averages of *B* are from Lockwood et al. (1999; L1999), Svalgaard and Cliver (2005; IDV05), Rouillard et al. (2007; R2007), Lockwood et al. (2009a; L2009), and Svalgaard and Cliver (2010; IDV09). Filled black circles are annual means of directly observed *B*. (b) A figure similar to (a) from Lockwood and Owens (2011). Plots are from Rouillard et al. (2007; REA07), Lockwood et al. (2009a; LEA09), and Svalgaard and Cliver (2010; SC10). The yellow curve is the correct reconstruction of solar wind *B* based on Lockwood et al. (2009) (cf., yellow curve in panel (a)), and solid black circles are annual means of observed *B*

Usoskin et al. (2016; Fig. 12(d)). In the first method, designated $B[\text{SSN}^{1/2}]$, *B* is assumed to be linearly correlated to the square root of sunspot number (Wang and Sheeley 2003; Wang et al. 2005; Svalgaard and Cliver 2005). The second method ($B[\text{OL2012}]$) used the model of Owens and Lockwood (2012) which assumes that open solar flux generation varies with the coronal mass ejection (CME) rate (with the sunspot number used as a proxy for the CME rate before the advent of coronagraph observations) and employs an *OSF* loss term that varies with the observed tilt angle of the heliospheric current sheet over the solar cycle and is assumed to be invariant from cycle to cycle. The resulting eight *B* series were then compared with *IDV*-based *B* (1845–2013) and a composite $B[\text{SSN}]$, shown in Fig. 12(e),

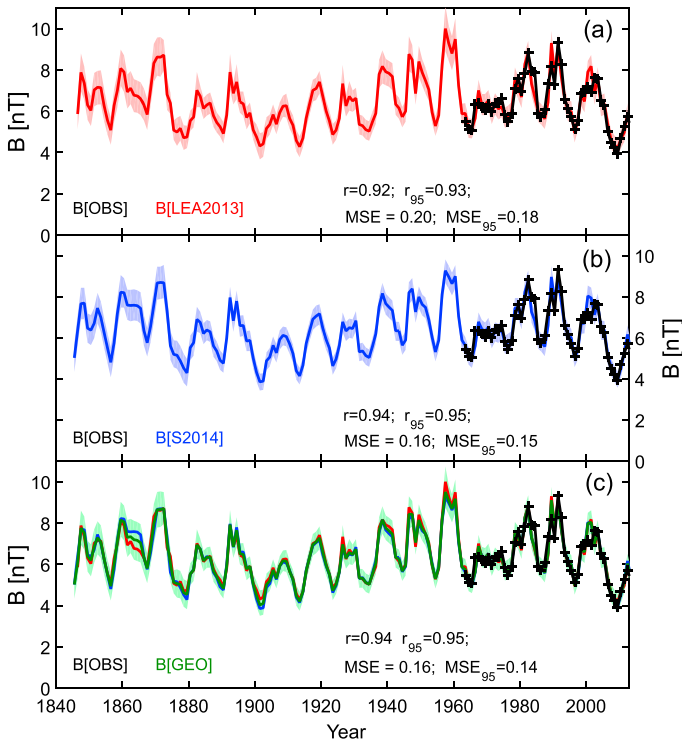


Fig. 11 Annual means of near-Earth solar wind B , 1845–2013. Black symbols show observed B , $B[\text{OBS}]$ from OMNI (<https://omniweb.gsfc.nasa.gov>) for the 1963–2013 interval. (a) Geomagnetic-based reconstruction of B from (Lockwood et al. (2013b); $B[\text{LEA2013}]$, red). (b) Geomagnetic based reconstruction of B from Svalgaard (2014; $B[\text{S2014}]$, blue). (c) $B[\text{GEO}]$ (green), a composite based on a weighted average of $B[\text{LEA2013}]$ and $B[\text{S2014}]$. Correlation coefficients (r) and mean square errors (MSE) relative to $B[\text{OBS}]$ are given. Shaded areas represent 90% confidence intervals. Subscripts “95” indicate values over the 1995–2013 interval. (From Owens et al. 2016a.)

was formed with slightly higher weights given to the series of Svalgaard and Schatten (2016) and Clette and Lefèvre (2016).

3.5.2 Long-Term Series of Solar Wind B Based on Cosmogenic Radionuclides

In Owens et al. (2016b) two independent cosmogenic based series for B (1750–~1990) were compared, using different methodologies, the first from McCracken and Beer (2015) and the second from Usoskin and colleagues (Usoskin et al. 2002; Alanko-Huotari et al. 2006; Kovaltsov and Usoskin 2010; Usoskin et al. 2015). Both series employ ^{10}Be concentrations from the Dye 3 and North GRIP Greenland ice cores. A key aspect of the McCracken and Beer (2015) time series is the correction (upward adjustment of B) necessitated by several large solar cosmic ray enhancements, either observed (1942–1956) or inferred (1816–1938), as well as by high-altitude nuclear explosions in 1962. It includes clusters of upper limit values of 2.5 nT for years near the depths of the Spörer, Maunder, and Dalton (ca. 1800)

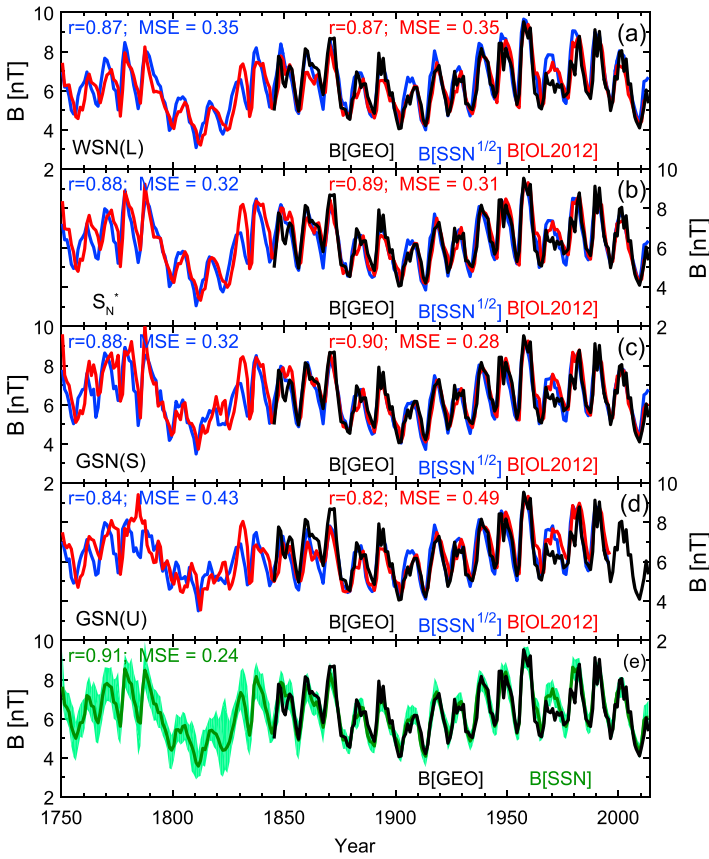


Fig. 12 Sunspot number based reconstructions of B over the period 1750–2013 compared with the 1845–2013 B [GEO] composite from Fig. 11(c); black lines). Blue lines show the results of the B [SSN $1/2$] reconstruction method, while red lines show reconstructions based on B [OL2012]. (a–d) Estimates of B based on: (a) WSN(L), (b) S_N^* , (c) GSN(S), and (d) GSN(U). (e) B [SSN], weighted composite of the eight individual B estimates. Correlation coefficients (r) and mean square errors (MSE) relative to B [GEO; 1945–2013] are given (adapted from Owens et al. 2016a)

minima.⁵ Figure 3 in Owens et al. (2016b) shows that the Usoskin series lays consistently below the McCracken and Beer (2015) series from 1750 to ~1900.

The McCracken and Beer (2015) annual time series for B extends from 1391–1983 and can be compared over this interval with the long-term (0–2000) series of the modulation potential (ϕ) obtained by Muscheler et al. (2016) based on annual measurements of ^{14}C concentrations in tree rings to 1950 and neutron monitor measurements thereafter. The modulation potential has units of MV and is a measure of heliospheric resistance to incoming cosmic rays (see, e.g., Herbst et al. 2010, 2017; Beer et al. 2012). The time series of magnetic field strength by McCracken and Beer (2015) and of the solar modulation potential by Muscheler et al. (2016) are based on numerical models to describe the ^{10}Be and ^{14}C measurements, respectively. The results strongly depend on the Local Interstellar

⁵Spörer (1412.0, 1420.0, 1421.0, 1436.0, 1442.1, 1448.4, 1450.3, 1451.1, 1560.1, 1461.9, 1531.6); Maunder (1681.0, 1692.7, 1693.6, 1694.6, 1696.0, 1697.0, 1697.8, 1698.7, 1704.6, 1705.9); Dalton (1809, 1810).

Spectrum (LIS) on which the computations are based. Since the end of 2013, after Voyager 1 crossed the outer boundary of our solar system, at least four new LIS have been proposed in the literature. The choice of the LIS model leads to differences in the production rate values of the cosmogenic radionuclides of up to 20% (see Herbst et al. 2017). Thus, in order to compare the McCracken and Beer time series of B with the Muscheler et al. ϕ -series, it is necessary to base both records on the same LIS model. Here we use the LIS from Herbst et al. (2017), which updates the LIS model of Potgieter et al. (2014) used by Muscheler et al. (2016), by taking the Voyager 1 measurements (see Stone et al. 2013; Webber and McDonald 2013) into account.

In order to describe the modulation of galactic cosmic ray (GCR) transport in the heliosphere, we use the Force-Field approximation of Gleeson and Axford (1968). The transport can be described as a quasi-steady-state balance between radially inward diffusion through interplanetary magnetic field irregularities with a diffusion coefficient κ , and a radially outward convection with the solar wind speed v_{sw} , depending on only one free parameter, the solar modulation parameter ϕ . As discussed in Caballero-Lopez and Moraal (2004), ϕ can be given by $\phi(r, t) = \int_r^{r_b} \left(\frac{v_{sw}(r', t)}{3\kappa(r', t)} \right) dr'$. By assuming $\kappa \propto B_{IMF}^{-\alpha}$ according to Steinhilber et al. (2010) the interplanetary magnetic field strength can be given by:

$$B_{IMF}(\phi, t) = B_{IMF,0} \left(\frac{\phi(t)}{\phi_0} \right)^{\frac{1}{\alpha}} \cdot \left(\frac{v_{sw}(t)}{v_{sw,0}} \right)^{-\frac{1}{\alpha}}, \quad (3)$$

where $B_{IMF,0}$, $v_{sw,0}$, and ϕ_0 represent the mean values of the magnetic field strength, solar wind speed, and solar modulation parameter during the instrumental era. Thereby, the time-dependent solar wind speed $v_{sw}(t)$ can be described by a linear relation between solar wind speed and ϕ : $v_{sw}(t) = m\phi(t) + q$, with $m = 0.23 \text{ km s}^{-1} \text{ MV}^{-1}$ and $q = 303 \text{ km/s}$. Using this equation, ϕ -reconstructions by different groups can be used to reconstruct the temporal variation of B_{IMF} . Based on OMNI2 data from 1963 to 2008, Steinhilber et al. (2010) used $\phi_0 = 615 \text{ MV}$, $B_{IMF,0} = 6.6 \text{ nT}$, $v_{sw,0} = 446 \text{ km/s}$ and $\alpha = 1.8 \pm 0.3$ in order to convert the ϕ -reconstructions of Steinhilber et al. (2008) into B . Note, however, that all parameters strongly depend on the time interval over which the measurements were taken, and that in particular ϕ_0 and α also strongly depend on the LIS model on which the ϕ -reconstructions are based. Thus, only B_{IMF} records which include the most recent measurements and which are based on same LIS model should be compared with each other.

We update the investigations by Steinhilber et al. (2010) by (a) including OMNI2 data from 2008 to 2016 and (b) converting ϕ -reconstructions to the LIS model of Herbst et al. (2017), in the following denoted as ϕ_{HE17} , in order to achieve comparability among the existing B_{IMF} records.

The following steps were performed:

1. Based on the measurements from 1963 to 2016 the mean values of the interplanetary magnetic field and the solar wind speed change to $B_{IMF,0} = 6.4 \text{ nT}$ and $v_{sw,0} = 438 \text{ km/s}$, respectively. The mean value of the updated solar modulation parameter is given by $\phi_0 = \phi_{HE17} = 678 \text{ MV}$. The exponent α is the only free parameter in the model by Steinhilber et al. (2010). By fitting Eq. (3) to the OMNI2 observations via least square regression we found α to be in the order of 1.25 ± 0.3 . The connection between ϕ and B_{IMF} (measurements: filled triangles; computations using Eq. (3): red line) is shown in Fig. 13(a).
2. To validate our results, we compare a B time series derived from a ϕ -reconstruction based on the Oulu Neutron Monitor measurements (see e.g., Usoskin et al. 2011) with a corresponding series based on the ϕ -reconstruction of Muscheler et al. (2016). In order

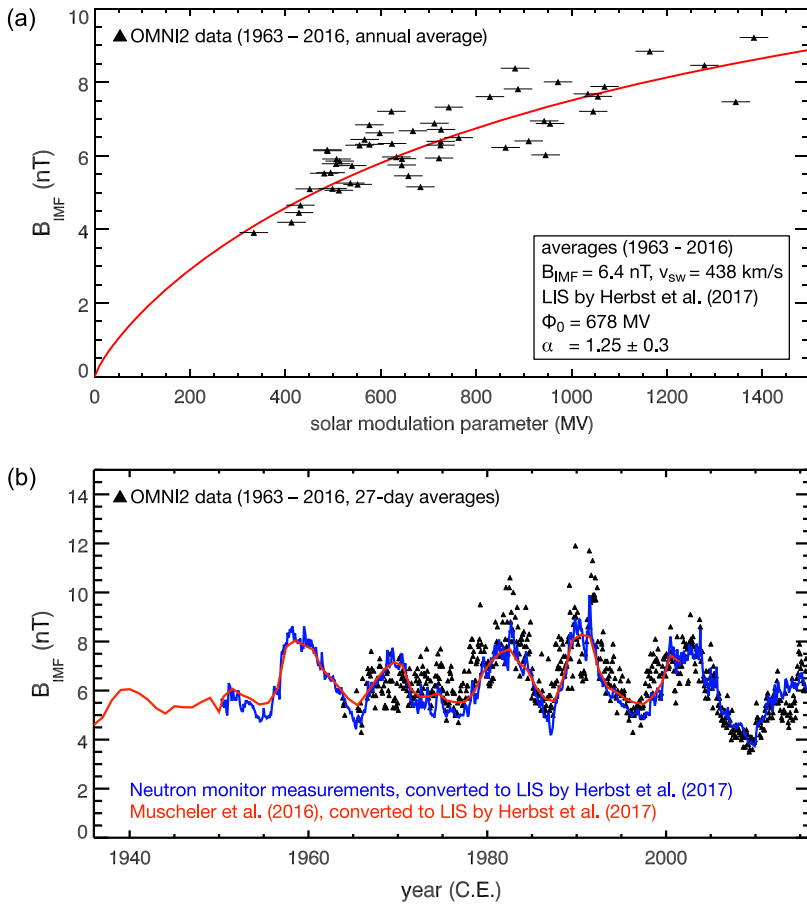


Fig. 13 (a) Scatter plot of B_{IMF} (IMF = Interplanetary Magnetic Field) as a function of the solar modulation parameter ϕ for 1963–2016, with red regression line (see Eq. (3)). (b) Comparison of the temporal variation of B_{IMF} based on monthly NM data (Usoskin et al. 2011; blue line) and annual ^{14}C data (Muscheler et al. 2016; red line). Black triangles represent 27-day averages of the OMNI2 B_{IMF} data for 1963–2017

to do so, we first converted the two ϕ -records, which depend on different LIS models, to ϕ_{HE17} . The ϕ -record of Usoskin et al. (2011) is based on the LIS model of Usoskin et al. (2005, ϕ_{US05}), while the record of Muscheler et al. (2016) is based on the LIS model of Potgieter et al. (2014, ϕ_{PG14}). To make the conversions, we used the linear regression functions $\phi_{HE17} = 1.025 \cdot \phi_{US05} + 24.18$ MV and $\phi_{HE17} = 1.025 \cdot (\phi_{PG14} - 28.0 \text{ MV}) / 1.029 + 24.18$ MV (see Herbst et al. 2017). Based on these new ϕ -values and Eq. (3), a reconstruction of B_{IMF} for both records can be performed. The good agreement between the measured B_{IMF} time series (filled triangles; 27-day averaged OMNI2 data) and those calculated from the Oulu NM data (Usoskin et al. 2011; blue line) and ^{14}C measurements (Muscheler et al. 2016; red line) is displayed in Fig. 13(b).

3. The ^{10}Be based B record of McCracken and Beer (2015) uses the LIS model by Castagnoli and Lal (1980). To scale this record to reconstructions based on the LIS by Herbst et al. (2017), we performed step 1) and 2) for a B_{IMF} reference proxy based on the LIS

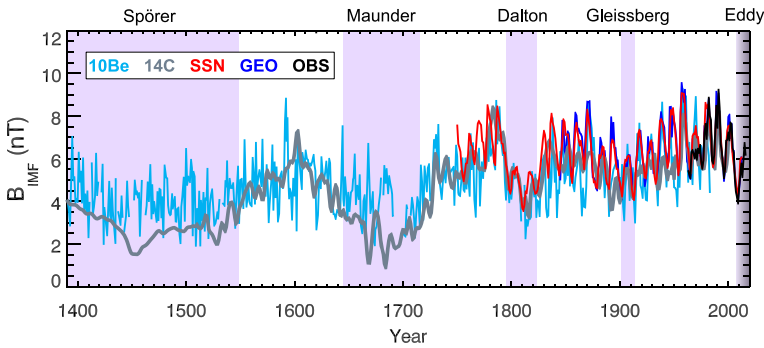


Fig. 14 Plots of solar wind B from 1390–2016 based on ^{10}Be (McCracken and Beer 2015; 1391–1983), ^{14}C (Muscheler et al. 2016; 1390–2002), sunspot number (Owens et al. 2016a; 1750–2013), geomagnetic IDV index (Owens et al. 2016a; 1845–2013), and spacecraft observations (1965–2016). The trace for the ^{14}C based B series is made thicker to facilitate comparison. For the ^{10}Be time series, values corrected for solar cosmic ray events during the 1775–1983 interval (and also for the effects of nuclear tests in 1962) are used, and upper limit values of 2.5 nT for years listed in Footnote 5 are not plotted. The times of the Spörer and Maunder Grand Minima are indicated along with those of subsequent Gleissberg-type minima

by Castagnoli and Lal (1980) with $\phi_0 = \phi_{CL80} = 611$ MV and $\alpha = 1.52 \pm 0.3$. With the resulting difference between $B_{IMF,CL80}(\phi, t)$ and $B_{IMF,HE17}(\phi, t)$, a rescaling is possible.

Figure 14 contains the independently-constructed time series for solar wind B of McCracken and Beer (2015; light-blue line) and Muscheler et al. (2016; gray) that are based on ^{10}Be and ^{14}C , respectively, over the ~ 1400 –2000 interval. For comparison, we have also added the ~ 170 -yr composite sequence of B based on geomagnetic data ($B[\text{GEO}]$, Fig. 11(c); dark blue line) and the sunspot number based ~ 260 -yr series of B ($B[\text{SSN}]$, Fig. 12(e); red); and the 1965–2016 record of direct observations ($B[\text{OBS}]$; black). The nominal dates of the Spörer and Maunder Grand Minima, based on the sunspot number, are indicated along with those of the less-pronounced Gleissberg-type minima ca. 1800 (Dalton minimum, 1798–1823), 1900 (Gleissberg minimum, 1900–1913), and 2010 (Eddy minimum; 2008–?). We have thickened the trace of the ^{14}C based series to increase its visibility. Compared to the other plotted series, its peak values are significantly lower than those of the other series from ~ 1850 –1950. Also noteworthy are the higher values of B for the McCracken and Beer (2015) series during the two Grand Minima. The large year-to-year variability of the ^{10}Be based series reflects in part the $\sim 20\%$ uncertainty for any given year (Owens et al. 2016b). As McCracken and Beer (2015) point out, increasing the number of long-term ice cores from two to five, with two of the new cores coming from the Antarctic, will result in a considerable reduction of noise in the ^{10}Be -based record for B . The more gradual year-to-year variation of ^{14}C -based B reflects the extended and complex path from creation to sequestration of ^{14}C in tree rings vs. the more rapid deposition of ^{10}Be in ice cores (Beer et al. 2012).

3.5.3 Composite B Series (1391–1983)

In Fig. 15, we have concatenated the following time series for solar wind B : direct observations (1965–2016), geomagnetic-based (1845–1964; Owens et al. 2016a); sunspot-based (1749–1844; Owens et al. 2016a); cosmogenic-nuclide based (1391–1748; McCracken and Beer 2015; Muscheler et al. 2016). This figure represents the state of the art in our knowledge of the last ~ 600 years of solar wind B . Uncertainties increase for each link of the

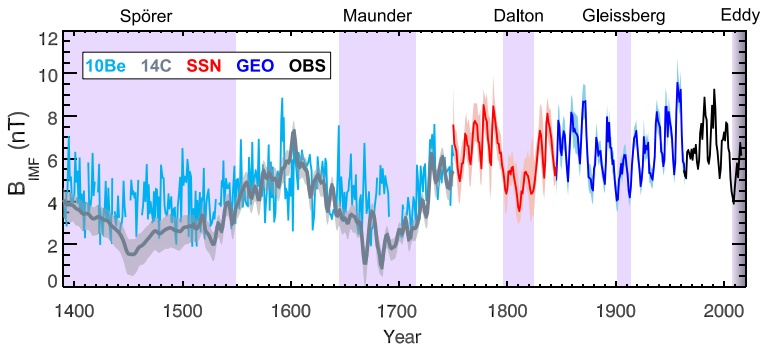


Fig. 15 Composite plot of solar wind B , with uncertainties, from 1390–2016 based on cosmogenic ^{10}Be (McCracken and Beer 2015; 1391–1748), ^{14}C (Muscheler et al. 2016; 1390–1748), sunspot number (Owens et al. 2016a; 1749–1844), geomagnetic data (Owens et al. 2016a; 1845–1964), and from observations in space near-Earth (1965–2016). Upper limit values of 2.5 nT in the McCracken and Beer (2015) for ~ 20 years (total) during the Spörer and Maunder Minima are not plotted (see Footnote 5). The times of the Spörer, Maunder, Dalton, Gleissberg, and (proposed) Eddy minima are indicated

chain as one goes back in time—from directly observed B , through time series based on geomagnetic data, sunspot number, and cosmogenic nuclides, in turn.

4 Recent Developments on the Maunder Minimum and the Floor in Solar Wind B

The low inferred values of sunspot activity and solar wind B during the Maunder Minimum mark it as a particularly important epoch, accounting for much of the observed/inferred range of long-term solar activity since ~ 1400 (Fig. 15). Recently, Zolotova and Ponyavin (2015, 2016) have argued that the Maunder Minimum may not be as grand as currently thought. They suggested that 11-yr peak annual averages of daily group counts for this period might range from ~ 3 –8 in contrast to the values of < 0.2 obtained by Hoyt and Schatten (1998a, 1998b) for the core years from 1645–1700. In other words, the Maunder Minimum might have looked more like a typical Gleissberg minimum, then a “Grand” minimum. The thrust of their argument was that, in general, the scientists who reported spots were not interested in tabulating their numbers but focused instead on round spots as possible evidence of intra-Mercurial planets (which partially motivated Schwabe’s observations), or large spots to provide insight on the nature of spots, or reported only haphazardly, e.g., as an occasional by-product of meridian transit observations. They also raised the issue of the inhibiting effect of contemporary theological support for Aristotelian views of an immaculate Sun. These arguments were rebutted by Usoskin et al. (2015) with a variety of data including “[...] the fraction of sunspot active days, the latitudinal extent of sunspot positions, auroral sightings at high latitudes, cosmogenic radionuclide data [including ^{44}Ti from meteorites for which interpretations of measurements do not need to take atmospheric transport and deposition processes into account as is the case for ^{10}Be and ^{14}C] as well as solar eclipse observations [...]” in addition to considerations of “[...] peculiar features of the Sun (very strong hemispheric asymmetry of sunspot location, unusual differential rotation and the lack of the K-corona) that imply a special mode of solar activity during the Maunder minimum.”

The low end of the range of inferred B values during the Maunder Minimum is of interest in relation to the putative floor in solar wind B of Svalgaard and Cliver (2007a). Cliver and

Ling (2011) used “(i) a relationship between solar polar-field strength and yearly averages of B for the last four 11-year minima (B_{MIN}), and (ii) a precursor relationship between peak sunspot number for cycles 14–23 and B_{MIN} at their preceding minima” to derive a reduced floor value of ~ 2.8 nT to which the solar wind in the ecliptic would drop if the Sun’s 11-yr cycle ceased. This value is in reasonable agreement with minimum yearly values in Fig. 15 from McCracken and Beer (2014, 2015) for both the Maunder and Spörer Grand Minima, but it lies above those of Muscheler et al. (2016) as well as recently modeled values for B during the Maunder Minimum. Even for the McCracken and Beer (2015) series, it must be noted that there are concentrations of years (not plotted in Fig. 15) at the depths of the Maunder and Spörer minima with upper limit values of 2.5 nT.

In an output from the ISSI team meetings, Riley et al. (2015) used a global thermodynamic MHD model to deduce that during the deepest part of the Maunder Minimum, the corona was “devoid of any large-scale structure, driven by a photospheric field composed of only ephemeral regions, and likely substantially reduced in strength.” Model-based estimates of solar wind Br for the two most extreme scenarios considered, viz., no solar polar field at sunspot minimum (absence of the 11-yr cycle) combined with a photosphere consisting of only small-scale ephemeral flux regions having “parasitic” magnetic polarities with average strength of either ± 10 G or ± 3.3 G, are 0.29 nT and 0.08 nT, respectively. For an assumed solar wind speed of ~ 300 km s $^{-1}$ (Cliver and Ling 2011; Cliver and von Steiger 2017; Owens et al. 2017), and using the formula in Fig. 5 of Cliver and Ling (2011) or the relationship in Fig. 11 of Lockwood and Owens (2011), these Br values translate into B values between ~ 0.5 to 2.0 nT. Modeled 11-yr minimum B values during the Maunder Minimum of ~ 1.5 nT and ~ 1.0 nT by Lockwood and Owens (2014; based on the *OSF* continuity equation of Owens and Lockwood 2012) and Owens et al. (2017; based on Owens and Lockwood 2012, and the three-dimensional magnetohydrodynamic model of the solar corona of Linker et al. 1999), respectively, fall within this range of values. These time series for B show the continuation of the cycle during the Maunder Minimum deduced by Beer et al. (1998) and Berggren et al. (2009), however, so a true floor level presumably would be lower since the cycle requires the presence of solar polar fields at 11-yr minima that will add to solar wind B at these times (Svalgaard et al. 2005). In fact, in another recent determination of B for the Maunder Minimum that begins with a continuity equation for the open solar flux, Rahmanifard et al. (2017), determined that any floor in solar wind B during this period could not be $\gtrsim 1.5$ nT and could be as low zero nT.

Observationally, we note the absence in Fig. 14 of the downward 40-yr spike to ~ 0 nT in B ca. 1500 seen in Fig. 9 for the Spörer Minimum, along with similar downward spikes in the modulation potential to values less than zero for both the Maunder and Spörer minima in Fig. S13 of Steinhilber et al. (2012).

5 Conclusions

5.1 Summary

We reviewed the evolution of thinking on time series for the sunspot number and solar wind B . The first of these has a research history going back over 400 years, the second of only ~ 50 years. Both fields have undergone intense development over the past two decades.

Key developments in sunspot research during this time include the development of the group sunspot number (GSN) by Hoyt and Schatten (1998a, 1998b), the sunspot number workshops of 2011–2015 (Cliver et al. 2013a, 2015; Clette et al. 2014), and independent

work on sunspot number time series (e.g., Lockwood et al. 2014c, 2014d, 2016d, 2016e; Usoskin et al. 2016; Willamo et al. 2017; Chatzistergos et al. 2017) that they triggered. Recent progress includes: (1) uncovering of inhomogeneities in both WSN (e.g., Svalgaard 2010, 2012; Leussu et al. 2013; Clette et al. 2014; Clette and Lefèvre 2016) and GSN (Clette et al. 2014; Cliver and Ling 2016; Cliver 2017), (2) a new group count data base (Vaquero et al. 2016), and (3) the introduction of novel reconstruction methods (e.g., Usoskin et al. 2016). This story is ongoing, with work in progress on reconciling, in so far as possible given the difference in the base formulae for the two series (Eqs. (1) and (2)), the recent proliferation of sunspot number time series. This effort will lead to new versions of both the Wolf and group sunspot number.

The key advances on construction of a long-term solar wind B time series include the seminal paper by Lockwood et al. (1999) that re-energized the field of space climate, the development of the long-term interdiurnal variability index of geomagnetic index by Svalgaard and colleagues (Svalgaard et al. 2003; Svalgaard and Cliver 2005), the ISSI International Team (2012–2013) on long-term solar and solar wind reconstruction (Owens et al. 2016a, 2016b), and the development of long-term high-time resolution series by McCracken and Beer (2015; from 1391–1983 for solar wind B) and Muscheler et al. (2016; from 0–2000 for modulation potential Φ), based on cosmogenic nuclides. For the solar wind B time series, we gave a detailed account of the path from Lockwood et al. (1999) to the present, as a case study of what one scientist memorably called “the truly gritty, uncertain and fun nature of scientific research” (Cliver and van Driel-Gesztelyi 2010).

Despite initial resistance, the work of both Lockwood and Svalgaard found relatively rapid acceptance. The Lockwood et al. (1999) report that the underlying open solar flux (the minimum-to-minimum variation) could change by a factor of two over 100 years was shown to be conservative as a comparison of directly-observed annual B_r values at cycle minima in 1986 (2.42 nT) and 2009 (1.25 nT) (Lockwood et al. 2009a; Cliver and Ling 2011), revealed a “reverse direction rise” of $\sim 95\%$ (or $\sim 52\%$ fall) over two solar cycles. Whether such changes in the OSF as that from 1986–2009 or the approximate doubling of the OSF during the first half of the 20th century represent random secular variations or are manifestations of longer cyclic (e.g., Gleissberg-type) behavior remains to be determined. Svalgaard’s development of the IDV index from Bartels’ u index, and his discovery of its relationship to near-Earth IMF (Svalgaard et al. 2003), became the basis for the reference geomagnetic-based long-term time series of solar wind B (Owens et al. 2016a).

The Maunder Minimum remains a lively field of research on both solar and solar wind activity. In regard to the Sun, the key question involves the level/duration of low sunspot activity: Was the Maunder a Grand Minimum (Usoskin et al. 2015), or more in the run of a Gleissberg-type centennial variation (Zolotova and Ponyavin 2015, 2016), or something in between? For the solar wind, a prominent question involves the existence of a floor, with proposed levels dropping from the original ~ 4.6 nT value of Svalgaard and Cliver (2007a) to the possibility of no floor recently modeled by Rahmanifard et al. (2017).

5.2 Lessons Learned

The efforts to obtain high-confidence long-term time series for solar wind B (Sect. 2) and the sunspot number (Sect. 1) suggest the following guidelines for the ongoing work on the sunspot number:

(1) *Nullius in verba* (take nobody’s word for it), the motto of the Royal Society, applies. This is a scientific truism but it was violated in the case of the Hoyt and Schatten (1998a, 1998b) group sunspot number, which was not independently vetted and found wanting (Cliver and Ling 2016; Cliver 2017) until nearly two decades after its introduction. The

lesson of the need for scrutiny is now being applied to all six of the newly modified or conceived sunspot number time series.

(2) For widely-used time series, the entire community must be involved. This was not the case for the sunspot number workshops and it only became so after the publication of the new time series by SILSO. If there is a general lesson here, it is the need to truly work, i.e., to publish, together. That way, all have ownership of the process, and the result.

(3) Reaching consensus takes time, approximately 15 years were required to reach the present state for solar wind B , and six so far for the sunspot number, with an estimate of two-to-three more needed for completion.

(4) There is always room for improvement. Error bars can be reduced as evidence accumulates. Versioning is a healthy and humbling concept. Continuous monitoring is required to preserve homogeneity. Formulate a prescribed mechanism for implementing and sanctioning updates. All of these precepts and practices apply for the nascent 3.0 versions of the S_N and GSN time series. The value of a single accepted time series, be it solar wind B or sunspot number, is akin to that of an established paradigm for a field in that it provides a framework against which new ideas and data can be measured.

(5) While ancillary or proxy data such as geomagnetic based solar B can be used to corroborate and guide the reconciliation of the various new sunspot number time series, it should be used in their actual derivation solely as a last resort, i.e., if there is no other way through a gap in the sunspot record. Before 1610, the proxy cosmogenic radionuclide data is the only proven way to reliably extend the solar activity record. A key end goal of the current sunspot recalibration effort is to provide guidelines and constraints for a reliable millennial-scale record of solar activity based on the paleo-cosmic-ray record.

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