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The 1859 space weather event: Then and now

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Abstract

The 1859 space weather event, combining the first solar flare ever reported with arguably the largest geomagnetic storm ever observed, provided a dramatic opening to a new area of Sun–Earth studies. Here I describe solar science at the time of the discovery of the flare, recount the observation, and trace the developments that led to the correct interpretation of the 1859 solar-terrestrial event by Bartels in 1937. A "fast forward" takes us to the present time when advances in modeling and increasing concern with space weather have prompted renewed interest in a classic observation.

Keywords: 1859; Carrington event; Space weather; White-light flare; Geomagnetic storm

1. Introduction

Why, after nearly 150 years, do we still care about the 1859 solar flare and the ensuing space weather event? There are three reasons. Historically, the white-light flare that R.C. Carrington and R. Hodgson observed on 1 September 1859 was the first flare ever reported and also the first to be linked to a terrestrial response. From a practical consideration, the September 1859 space weather event was one of the largest – if not the largest (e.g., McCracken et al., 2001; Tsurutani et al., 2003) – ever observed and thus represents a working "worst case scenario" (Cliver and Svalgaard, 2004) of solar-terrestrial interaction for spacecraft designers and mission planners. Finally, recent advances in understanding and modeling make it possible to take a modern look at the 1859 event to estimate the solar and solar wind parameters and simulate the response of the magnetosphere and ionosphere to an extreme solar wind disturbance.

In this paper, the emphasis will be on the first of these reasons, the historical aspect. I will first place the observation of the 1859 flare in the context of solar research in the early Victorian era, focusing on the period from ~1840 to 1860 that encompassed a number of remarkable discoveries and witnessed a general resurgence of interest in the Sun. Then the observation of the 1859 solar event and the accompanying geomagnetic activity will be recounted and an assessment given of the impact of the flare-storm observation on the understanding and acceptance of the Sun–Earth connection during the 19th century. A review of the instrumental advances and scientific discoveries that allowed Bartels to give a complete description of the Carrington solar-terrestrial event in 1937 will be followed by a "fast forward" to the present epoch.

While the focus in this paper is on the 1859 event "then", the emphasis in the subsequent papers in this issue will be on the "now", applying what we have learned in recent years to give a current view of a classic event. The workshop held on the Carrington event at the University of Michigan on 2–3 October 2003 was timely because it was quickly followed by major solar events in late October and early November that mimicked certain aspects of the 1859 event, e.g., the short (<20 h) Sun–Earth transit time of the disturbance. This recent,

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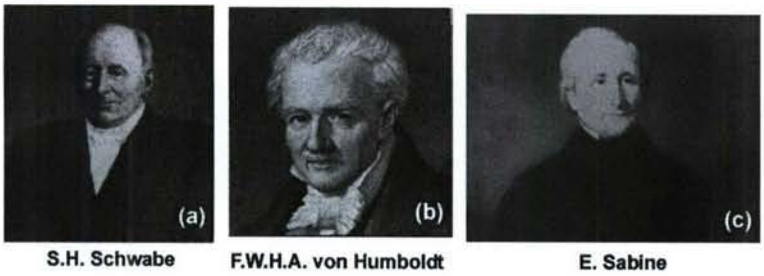

Fig. 1. Three principals in the birth of solar-terrestrial physics: (a) S.H. Schwabe (1789–1875), a pharmacist from Dessau who discovered the sunspot cycle in 1843: (b) Baron F.W.H.A. von Humboldt (1769–1859), a prominent and wide-ranging German scientist who popularized Schwabe's discovery of the sunspot cycle; and (c) Sir Edward Sabine (1788–1883), a superintendent of British colonial observatories who linked Schwabe's sunspot cycle to a corresponding cycle in geomagnetic activity.

well-observed, activity provides an opportunity for comparative analysis with the 1859 event and a check on model output.

2. The 1859 space weather event occurred during a time of renewed interest in the Sun and its spots

Following the discovery of sunspots by Galileo and others early in the 17th century, there was relatively little progress on this topic until the middle of the 19th century – the most important result in the interim was Wilson's (1774) inference that sunspots represented depressed regions ("excavations") of the solar surface. The relative absence of spots during the latter half of the 17th century (the Maunder Minimum; Eddy, 1976)[1] certainly contributed to this slow pace of progress.

The mid-19th century, however, witnessed a rapid advance in sunspot studies. Samuel Heinrich Schwabe (Fig. 1(a)), a pharmacist from Dessau in Germany, began to make daily counts of sunspots in 1826. Schwabe (1857) attributed his study of the Sun to "my old and valued friend Harding of Göttingen, who wrote to me that there was a great want of physical observations of the sun, that the subject presented an almost unworked field, and that labour therein might be rewarded by the discovery of a planet interior to Mercury." In 1829, Schwabe sold his shop so he could devote full time to his scientific investigations. Schwabe's systematic observation of the Sun led him to identify a decennial cycle in sunspot activity (later refined by Wolf to 11 years) that was announced in 1844 in Astronomische Nachrichten (Schwabe, 1844). His work, however, attracted little attention until it was republished in extended form (to 1850) by the elderly and highly influential German scientist Baron Alexander von Humboldt (Fig. 1(b)) in volume 3 of his Kosmos series in 1851.

The immediate beneficiary of von Humboldt's popularization of Schwabe's result was Colonel Edward Sabine (Fig. 1(c)), a leading exponent of magnetic observations and superintendent of British magnetic observatories at St. Helena, the Cape of Good Hope, Hobarton (presently Hobart), and Toronto (see Cawood (1979) on the "Magnetic Crusade"). In his analysis of the data from the widely separated Hobarton and Toronto stations, Sabine (1852) discovered that minima (in 1843) and maxima (1848) in annual averages of the frequency and intensity of magnetic storms corresponded exactly with Schwabe's minimum and maximum sunspot years. Sabine was fortunate that the six-year period of magnetic data (1843–1848) he analyzed was phased such that it allowed him to deduce the 11-year solar cycle period.[2] He was doubly lucky in that the correspondence between geomagnetic activity and the sunspot cycle is generally not as close as it happened to be for the period he analyzed (Ellis, 1900). A third favorable aspect involved the priority of the discovery. Sabine's wife translated volume 3 of Kosmos (von Humboldt, 1851) from German for publication in England (Meadows and Kennedy, 1982); early access to Schwabe's updated result may have been crucial because Sabine's report preceded independent discoveries of the Sun-geomagnetic activity link by Wolf (1852a,b) and Gautier (1852), both from Switzerland, by only a few months. The discovery of the sunspot cycle period in the geomagnetic activity record is generally taken to mark the birth of solar-terrestrial physics.

Schwabe also benefitted from the widespread awareness of the sunspot cycle brought about by Kosmos. In 1857, with Carrington's support, Schwabe was awarded the Gold Medal of the Royal Astronomical

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[1] Eddy's work on the sunspot drought from 1645 to 1715 had precursors in the work of Spörer (1889a,b) whose work was summarized and publicized by Maunder (1890, 1894, 1922). Eddy named the 17th century sunspot minimum period after Maunder and an earlier inferred minimum from ~1460 to 1550 after Spörer.

[2] In fact Sabine initially had analyzed only five full years of data, from July 1843 to June 1848. In a postscript added to his paper prior to publication, he analyzed additional data covering the interval from January 1841 to June 1843 and confirmed that the year 1843 corresponded to a true minimum in geomagnetic activity.

Society. Carrington personally delivered the medal to Schwabe in Germany.

Schwabe's finding of the sunspot cycle had motivated Carrington to look for additional regularities in sunspot activity (Carrington, 1863). Carrington's research, carried out at his private Redhill Observatory established south of London near Reigate in 1853, resulted in the discoveries of the latitude variation of sunspots over the solar cycle (Carrington, 1859a; later characterized as Spörer's law and represented as the Maunder butterfly diagram) and solar differential rotation (Carrington, 1859b). In the course of his daily sunspot observation on 1 September 1859, Carrington co-discovered, with Hodgson, a solar flare, as described in detail below.

The sunspot-related research of Schwabe, Sabine, and Carrington, with von Humboldt serving as a catalyst, greatly stimulated interest in the Sun.[3] The sunspot work was not the sole cause of a resurgence in solar research during this period, however. Observation of the Baily's Beads phenomenon (caused by sunlight shining between jagged mountain peaks on the moon near the beginning and end of totality (or annularity)) at the 1836 eclipse stimulated interest in the total eclipse of 1842, visible across southern and central Europe. Basic questions raised about the nature of the prominences ("protuberances") and corona at this eclipse resulted in well-observed European eclipses in 1851 and 1860, and helped to establish the tradition of eclipse expeditions for detailed solar (as opposed to lunar orbital or geographic position) studies. Observations of the 1851 eclipse enabled astronomers to determine that prominences were a solar, not lunar, feature and additionally led to the recognition of the chromosphere (initially called the "sierra") as a distinct layer of the solar atmosphere. Several more eclipses were required before the general acceptance, by ~1870, of the corona as a solar feature (rather than the result of scattering in the Earth's atmosphere). Kirchoff's and Bunsen's results, published beginning in 1859, marked spectroscopy as a third key line of research. Led by Kirchoff, Ångström, Lockyer, and others, spectroscopists mapped the solar spectrum, discovered helium, and identified emission lines that would in the following century give evidence of the million-degree corona.

3. The white-light flare of 1 September 1859 and associated geomagnetic activity

How does the Sun exert its influence on Earth's magnetism? A tantalizing clue presented itself on 1 September 1859 with the first observation of a solar flare. The observers of this historic event were Richard Christopher Carrington, son of a wealthy brewer and an eminent self-established astronomer,[4] and Richard Hodgson, a retired publisher and amateur scientist. Balfour Stewart was Director of Kew Observatory where the magnetic observations referred to by Carrington and Hodgson were made.[5] A map showing the relative locations of Carrington, Hodgson, and Stewart outside London is given in Fig. 2.

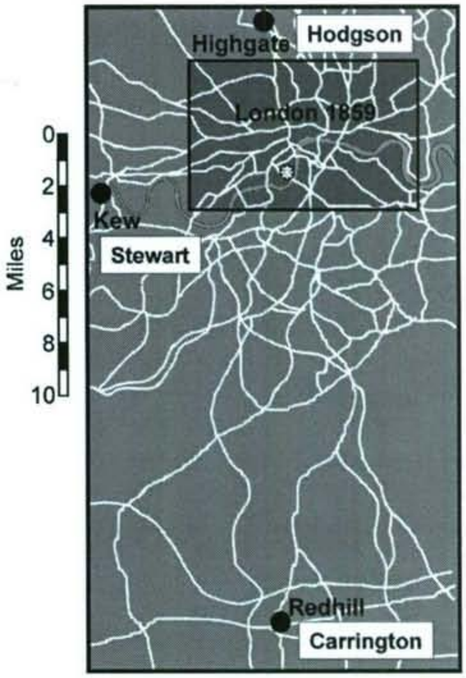

Fig. 2. Map of London and environs showing the locations of observers of the 1859 space weather event. The shaded region indicates the approximate city limits of London circa 1859. The star on the Thames river gives the position of the Houses of Parliament.

3.1. Description of a singular appearance seen in the Sun on 1 September 1859

No better account of the first observation of a solar flare can be given than that provided by Carrington himself, presented under the above title to the Royal Astronomical Society (R.A.S.) on 11 November 1859 (Carrington, 1860):

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[3] Key sources that trace the evolution of solar studies during the 19th century include: Clerke (1887), Newton (1958), Meadows (1970) and Hufbauer (1991).

[4] A biographical sketch of R.C. Carrington (1826–1875) is being prepared for Solar Physics. Anonymous (1876) gives an informative obituary and, more recently, Chapman (1998) places Carrington in the context of other "grand amateurs" of his time.

[5] The most complete magnetic records for this event of which we are aware (see Kimball (1960) for a partial list of stations that observed the disturbance) were made at Kew, Greenwich Observatory, and Colaba Observatory in Bombay (now Mumbai), India. Of these three, only the Colaba record (Tsurutani et al., 2003) does not go off-scale during the peak of the storm. The observations from Toronto (Loomis, 1859) do not include the first ~5 h of the storm.

"While engaged in the forenoon of Thursday, September 1, in taking my customary observation of the form and positions of the solar spots, an appearance was witnessed which I believe to be exceedingly rare. The image of the Sun's disk was, as usual with me, projected on a plate of glass with distemper of a pale straw color, and at a distance and under a power which presented a picture of about 11 in. diameter. I had secured diagrams of all the groups and detached spots ... when within the area of the great north group (the size of which had previously excited general remark), two patches of intensely white and bright light broke out, in the positions indicated in the appended diagram [Fig. 3] by the letters A and B, and of the forms of the spaces left white. My first impression was that by some chance a ray of light had penetrated a hole in the screen attached to the object-glass, by which the general image is thrown into shade, for the brilliancy was fully equal to that of direct sun-light; but, by ... causing the image to move by turning the R.A. handle, I saw I was an unprepared witness of a very different affair. I thereupon noted down the time by the chronometer, and seeing the outburst to be very rapidly on the increase, and being somewhat flurried by the surprise, I hastily ran to call some one to witness the exhibition with me, and on returning within 60 s, was mortified to find that it was already much changed and enfeebled. Very shortly afterwards the last trace was gone, and although I maintained a strict watch for nearly an hour, no recurrence took place. The last traces were at C and D, the patches having traveled considerably from their first position and vanishing as two rapidly fading dots of white light. The instant of the first outburst was not 15 s different from 11 h:18 min Greenwich mean time, and 11 h:23 min was taken for the time of disappearance."

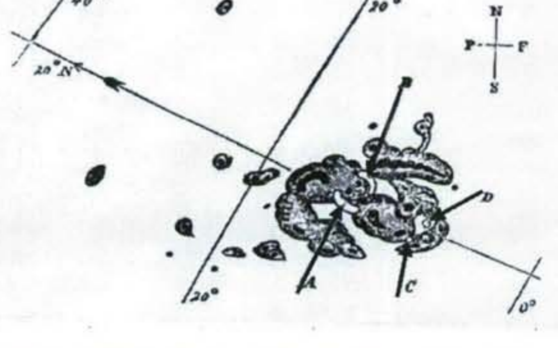

Fig. 3. Carrington's drawing of Sunspot Group 520 on 1 September 1859 (from Carrington, 1860). The initial locations of the white light emission are indicated by the arrows labeled A and B. The final positions at which white light emission was observed are indicated by arrows C and D. P = preceding and F = following, so solar west is to the left of the figure.

3.2. R. Hodgson confirms Carrington's observation

Fortunately Carrington's observation was confirmed by R. Hodgson. When Carrington became aware that Hodgson had also witnessed a remarkable solar phenomenon on 1 September, he "carefully avoided exchanging any information with that gentleman, that any value which the accounts may possess may be increased by their entire independence." Hodgson (1860) presented the following account entitled "On a curious appearance seen in the Sun" at the 11 November 1859 meeting:

"While observing a group of sunspots on the 1st September, I was suddenly surprised at the appearance of a very bright star of light, much brighter than the Sun's surface, most dazzling to the protected eye, illuminating the upper edges of the adjacent spots and streaks, not unlike in effect the edging of the clouds at sunset; the rays extended in all directions; and the centre might be compared to the dazzling brilliancy of the bright star α Lyrae when seen in a large telescope with low power. It lasted for some five minutes, and disappeared instantaneously about 11.25 a.m." (Hodgson presented a sketch, apparently no longer extant, of his observation at the meeting.)[6]

Today we recognize the "curious appearance" observed by Carrington and Hodgson as a white-light flare, a relatively rare occurrence indicating a particularly intense solar eruption. Neidig and Cliver (1983a) estimated that only about 8 white-light (>4000 Å) flares occurred per year for a ~2.5-year-period (June 1980–December 1982) following the maximum of sunspot cycle 21. For comparison, >9000 Hα flares of all sizes were reported during 1981.[7]

3.3. Both Carrington and Hodgson noted the association of the solar disturbance with geomagnetic activity

Carrington's (1860) article in the Monthly Notices of the R.A.S. is followed by a parenthetical comment, presumably supplied, or at least vetted, by Carrington as one of the Secretaries of the Society. It reads:

"Mr. Carrington exhibited ... a complete diagram of the disk of the sun at the time, and copies of photographic records of the variations of the three magnetic elements, as obtained at Kew, and pointed out that a

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[6] Like Schwabe and unlike Carrington, Hodgson observed the Sun directly through his telescope, using a darkened glass to protect the eye. Hodgson employed a transparent flat reflecting surface, placed diagonally in front of the focal plane, that greatly reduced the intensity of light incident on the eyepiece. This enabled him to use a glass of relatively light tint to guard against the Sun's glare (Hodgson, 1855; Dawes, 1860).

[7] The average sunspot number for the period from June 1980 to December 1982 was 133.9 in comparison with 93.8 for 1859, near the peak of solar cycle 10.

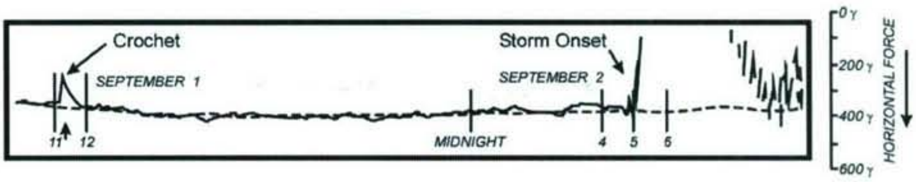

Fig. 4. The horizontal trace of the Kew magnetogram from 1012 UT on 1 September 1859 to 1010 UT on 2 September 1859 (after Stewart, 1861). The times of the prompt (magnetic crochet or solar flare effect) and delayed (geomagnetic storm onset) responses to the Carrington flare are indicated by arrows.

moderate but very marked disturbance took place at about 11 h:20 min a.m., of short duration; and that towards four hours after midnight there commenced a great geomagnetic storm [the Kew horizontal trace showing these two disturbances, marked by arrows, is given in Fig. 4], which subsequent accounts established to have been as considerable in the southern as in the northern hemisphere. While the contemporary occurrence may deserve nothing, he would not have it supposed that he even leans toward hastily connecting them. 'One swallow does not make a summer'."

Hodgson's statement on the associated geomagnetic activity was more prosaic, "The magnetic instruments at Kew were simultaneously disturbed to a great extent." Thus neither of the two solar observers pressed the point of a solar-terrestrial link for this event, although both Hodgson's comment and Carrington's use of the modifier "hastily" leave the door open to such a connection. Stewart (1861), in his presentation of the Kew magnetograms, partially reproduced in Fig. 4, was the most enthusiastic of the three principal observers of the first reported solar-terrestrial event when he wrote "If no connexion had been known to subsist between these two classes of phenomena [solar and geomagnetic], it would, perhaps, be wrong to consider this in any other light than a casual coincidence; but since General Sabine has proved that a relation subsists between magnetic disturbances and sun spots, it is not impossible to suppose that in this case our luminary was taken *in the act* [italics in the original]."

The magnetic deflection observed coincident[8] with the white-light flare in the 1859 event is a sudden ionospheric disturbance called a geomagnetic crochet (because of its hook line appearance) or, more commonly today, a solar flare effect (SFE). As seen in Fig. 4, the great geomagnetic storm beginning early on 2 September drove the Kew magnetometer traces off-scale. The storm was accompanied by a great low-latitude aurora visible from Santiago (Chile), Honolulu (Hawaii), and Wakayama (Japan) (Loomis, 1859–1861; Kimball, 1960).

3.4. Remarkable aspects of the 1859 space weather event

I have always found it remarkable that the first flare ever observed should be associated with arguably the largest space weather event ever documented. Historically, it seems to be asking a lot of a single event. The space weather effects (magnetic crochet, magnetic storm and aurora, solar particle event) of the 1859 solar eruption rank among the most extreme examples ever observed (Cliver and Svalgaard, 2004). While the sizes of these various impacts reflect the magnitude of the parent disturbance on the Sun, and therefore its observability, other white-light flares were observed during the 19th century – by techniques similar to that used by Carrington and Hodgson – for which the terrestrial responses were less impressive.[9] Thus there is no a priori reason why the 1859 space weather event had to be so large. The storm size did benefit from two factors: the location of the flare close to Sun center (N20 W12) and the occurrence of the event near the equinox (e.g., Svalgaard et al., 2002).

A second remarkable aspect of the Carrington solar-terrestrial event concerns a notable magnetic storm that preceded it on 28 August 1859. The 28 August event is one of only a handful of magnetic storms reported for the century preceding the International Geophysical Year (including the 2 September event) for which aurora were reported within ~30° of the geomagnetic equator (Silverman and Cliver, 2001).[10] The W12 solar source location of the 2 September storm implies that the 28 August storm originated at approximately E55-60 longitude – assuming the same source region as the Carrington storm and a short (for an ~E60 flare) 40-h solar wind propagation time (Cliver and Cane, 1996). Thus, under the further, common, assumption that the solar eruption propagated radially from the Sun, the solar

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[8] Stewart (1861) reported that the crochet "occurred as near as possible at 11:15 a.m. Greenwich mean time." The geomagnetic storm began 17.6 h later at 04:50 a.m. on 2 September (Bartels, 1937).

[9] Besides the Carrington flare, reported 19th century white-light flares occurred on 13 November 1872 (observed by Secchi), 17 June 1891 (Trouvelot), and 15 July 1892 (Rudaux) (Neidig and Cliver, 1983b). Only the last of these was accompanied by a great geomagnetic storm (Hale, 1892; Newton, 1943). The 1892 storm, however, is not listed among the seven storms – including the 1859 event – occurring between 1857 and 1938 that Chapman and Bartels, 1940 considered to be the most violent during that interval (see also Jones, 1955).

[10] The other events occurred in February 1872, September 1909, and May 1921.

wind disturbance responsible for the storm on 28 August would have struck Earth only a glancing blow. It is possible that if this solar eruption had been more "favorably" located relative to Earth, the violence of the associated geomagnetic storm would have exceeded that of the event beginning on 2 September.

Finally, it is noteworthy that the first flare ever reported was observed independently by two people, and thus immediately confirmed. However, this instantaneous confirmation (echoing that attending Sabine's discovery) did not translate into rapid acceptance or understanding of the apparent Sun–Earth connection presented by the 1859 event.

4. Interpreting the clue of Carrington's flare: Slow progress during the 19th and early 20th centuries

Carrington's reference to the 1859 solar disturbance as a "singular appearance" and his "one swallow" aphorism[11] anticipated the difficulty in establishing a solar-geomagnetic association for discrete events. While the 1859 event was prominently referred to throughout the 19th century (e.g., Armstrong, 1864; Proctor, 1871; Young, 1884; Thomson, 1893), the insight it offered was not fully realized until well into the following century.

The linkage of the 11-year solar and geomagnetic cycles by Sabine, Wolf, and Gautier in 1852 was updated by Ellis in 1880 to cover the intervening period.[12] Despite this update (Ellis, 1880), in which smoothed monthly averages of the daily ranges of the magnetic elements were shown to closely track the sunspot curve, the solar cycle correspondence of sunspot and geomagnetic activity was famously challenged, along with the reality of the flare-storm connection in the 1859 event, by Lord Kelvin (William Thomson) in a Presidential Address to the Royal Society in 1892. Thomson argued on the basis of an energy calculation that our star was "absolutely" incapable of powering even a moderate-sized magnetic storm through "magnetic action ... or ... any kind of dynamical action taking place within the sun, or in connexion with hurricanes in his atmosphere, or anywhere near the sun outside." He continued, "It seems as if we may also be forced to conclude that the supposed connexion between magnetic storms and sun-spots is unreal, and that the seeming agreement between the periods has been a mere coincidence." Thomson's energy analysis was correct in regard to his proposed mechanism – magnetic waves propagating in empty space – but his conclusion did not anticipate the possibility that solar plasmas and fields might be ejected by the Sun to cause geomagnetic storms.

A solar-geomagnetic link was not accepted without reservation until Maunder (1905) presented convincing evidence that the Sun's 27-day rotation period was present in the geomagnetic record. Maunder's analysis is shown in Fig. 5, a stacked plot of Carrington rotations from 1882 to 1903 with periods of elevated geomagnetic activity indicated by horizontal lines. Maunder was struck by the occasions (some of which have been circled in the figure) when geomagnetic disturbances repeated at 27-day intervals. He concluded, "That, therefore, which Lord Kelvin spoke of twelve years ago as 'the fifty years outstanding difficulty' [in the way of believing the Sun to be the direct cause of magnetic storms at Earth] is now rendered clear. Our magnetic disturbances have their origin in the Sun."

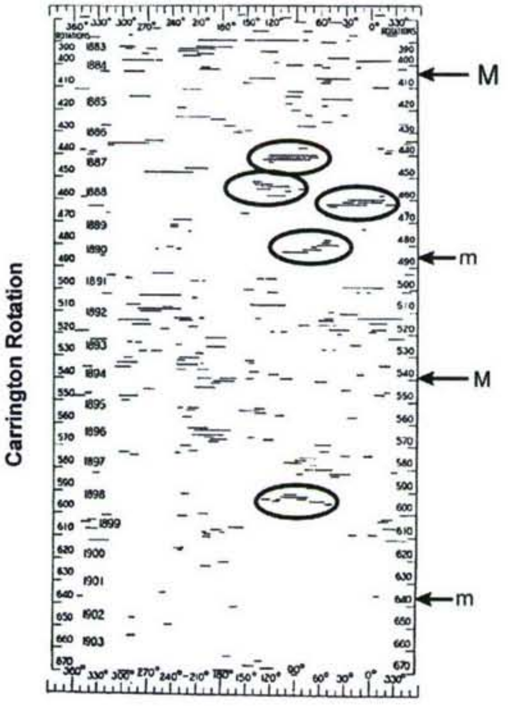

Fig. 5. A stack plot of Carrington rotations from 1882 to 1903 (after Maunder, 1905). The times of enhanced geomagnetic activity during each rotation are indicated by horizontal lines. Prominent examples of sequences of activity occurring at 27-day intervals (four or more rotations) identified by Maunder are circled on the figure. The times of sunspot maxima (M) and minima (m) (based on smoothed monthly sunspot numbers) are marked.

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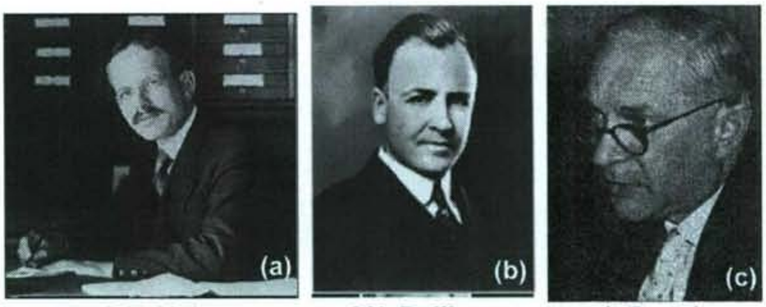
[11] Bartlett's Familiar Quotations (Bartlett, 1980) attributes this saying to Aristotle.

[12] The synchronicity of sunspot cycle and geomagnetic activity reported by Ellis (updated further in Ellis, 1898) that convinced most astronomers and geomagneticians of a Sun-magnetism link during the 19th century (Meadows, 1970) has an ironic aspect. The average daily range parameter (as defined by Ellis) is dominated by the regular variation, reflecting ionospheric currents driven by solar ionizing (X-ray and EUV) radiation. Thus the relationship between annual averages of the sunspot number and geomagnetic daily ranges is similar to that between sunspot number and the intensity of the solar 10-cm radiation. A key challenge for developers of geomagnetic indices (e.g., Mayaud, 1980) is to remove the regular variation and isolate the component due to the solar wind (corpuscular streams in Bartels' day). When that is accomplished, the agreement between the sunspot cycle and Earth's magnetic activity is less apparent.



G.E. Hale **J.H. Dellinger** **J. Bartels**

Fig. 6. Three scientists who helped to unravel the meaning of the 1859 solar flare and associated geomagnetic activity: (a) George Ellery Hale (1868–1938), a renowned American astronomer who invented the spectroheliscope and was instrumental in founding the worldwide solar flare patrol; (b) J. Howard Dellinger (1886–1962), an American radio scientist who discovered that fade outs on high frequency radio links were caused by ionizing radiation from solar flares; and (c) Julius Bartels (1899–1964), a German geophysicist who explained the prompt and delayed geomagnetic effects of the Carrington flare.

Maunder attributed sequences of 27-day recurrent storms to encounters by Earth with "a stream [with an average diameter of ~20°] which appears to be rotating with the same speed as the area [of the Sun's surface] from which it arises." While Carrington's establishment of a solar "prime meridian" provided the framework for Maunder's analysis (Fig. 5), Maunder's result refers primarily to 27-day recurrent storms rather than to non-recurrent sunspot-related storms such as the 1859 event. Maunder's proof that the Sun was the source of geomagnetic activity preceded the gradual recognition during the first half of the 20th century (Bartels, 1940; Allen, 1944; Newton and Milsom, 1954) that magnetic storms can originate in two distinctly different sources on the Sun: M-regions[13] (Bartels, 1932; later identified with coronal holes) and active/sunspot regions.

An earlier paper by Maunder (1892; see also Maunder, 1904) had pointed out that while the three largest geomagnetic storms occurring between 1873 and 1892 were associated with the three largest sunspot groups appearing during the same interval, there were other occasions when large spot groups were seen on the Sun and the magnets "scarcely fluttered". The 1859 event pointed the way out of this quandary but it lacked supporting evidence. A few other examples of discrete Sun–Earth connection events were observed during the 19th century (e.g., Hale, 1892; see Newton, 1940) but the solar and geomagnetic observations tended to be compartmentalized and the flare results were scattered in the literature.

5. New observations enabled Bartels to interpret the 1859 event in 1937

The principal problem was the lack of systematic flare observation. Between 1859 and 1925 only about 20 cases of great flares (class 3+ or "super flares" as designated by Newton (1943)), serendipitously observed, are documented in the literature (cf., Švestka and Cliver, 1992). These included: white-light flares, such as the Carrington event (Neidig and Cliver, 1983b); cases of brilliant reversals of lines observed with spectroscopes (Newton, 1940); and events observed with spectroheliographs. The spectroheliograph, invented by Hale (Fig. 6(a)) in 1892, worked by moving the entrance and line slits of a spectroscope in tandem across the Sun, making it possible (although somewhat cumbersome) to build up a photographic image of the Sun in the narrow emission lines in which flares are most prominent.

Between 1924 and 1929, Hale (1929) invented the spectrohelioscope that operated on the same principle as the spectroheliograph but in which the slits were rapidly oscillated so that a complete image of the sun could be obtained by eye through persistence of vision. This instrument (and successors based on narrow line filters) greatly facilitated flare observation.[14] Hale played a central role in founding a worldwide flare patrol based on the spectrohelioscope. Beginning in 1934, patrol results

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[13] Bartels (1932, 1940) used the term M-region to refer generally to those regions on the Sun that gave rise to magnetic storms (in this sense the M-regions were anticipated by Maunder's (1905) "magnetically active areas" on the Sun). Bartels noted that, "The identification of the M-regions with sunspots or other solar phenomena is possible in some cases only, while in many cases the M-regions lead, so to say, an independent life." This somewhat vague definition of M-regions evolved over the next decade to a position where sporadic intense storms (initiated by sudden commencements and favoring the solar maximum epoch) were associated with active regions and chromospheric flares and 27-day recurrent storms (gradual onsets and most prominent on the decline of the solar cycle) were attributed to the M-regions (Bartels, 1940; Chapman and Bartels, 1940; Allen, 1944; see also Greaves and Newton, 1929). However, at some level, a debate on whether M-regions were active or quiet regions on the Sun (e.g., Gulbrandsen, 1973) persisted until the discovery of coronal holes by spaceborne EUV and X-ray detectors.

[14] The frequency of reported large (3+) flares increased by approximately a factor of four from 1926 to 1942 in comparison with the 1859–1925 period (Newton, 1943). The increase in the reporting rate for smaller flares, those less likely to attract attention and be recorded in pre-spectrohelioscope years, would be greater.

have been regularly reported, initially in the Quarterly Bulletin of Solar Activity of the International Astronomical Union and more recently in the Solar-Geophysical Data publication of the US National Oceanic and Atmospheric Administration.

In 1931, Hale presented anecdotal evidence for a link between discrete solar events and geomagnetic storms. He collected and summarized the data for ~10 cases from 1859 to 1926 where solar eruptions[15] were closely followed by large geomagnetic storms (Hale, 1931). The subtitle of Hale's paper – "Solar eruptions and their apparent terrestrial effects" – reflects the cautious reserve with which astronomers regarded the flare-storm connection more than 70 years after Carrington's and Hodgson's observation. With the operation of the worldwide flare patrol, evidence accumulated that would soon dispel this uncertainty.

Hale's efforts to improve and systematize solar observations between 1892 and 1934 were paralleled by the work and suggestions of Goldstein, Fitzgerald, Birkeland, Lindemann, Chapman, Ferraro, and others to deduce the nature of the disturbance that propagated from the Sun to cause geomagnetic storms. Birkeland's (1896, 1908, 1913) terella experiments, in which a beam of "cathode rays" (electrons) created an aurora-like effect around a magnetized globe, permitted a visualization of the emerging "corpuscular hypothesis" [see Stern (1989) and Cliver (1994b) for reviews]. Chapman's employment of a charged beam in his outline of a theory of magnetic storms (Chapman, 1919) was promptly criticized by Lindemann (1919) who argued that the incident beam would have to be electrically neutral – what is today called a plasma. Lindemann's plasma beam was a key component of Chapman and Ferraro's (1931a,b, 1932, 1933) influential "New Theory of Magnetic Storms" which introduced the concept that came to be known as the magnetosphere. As a result of this ~50 year line of work, geomagneticians gradually accepted the corpuscular hypothesis as an article of faith (Dessler, 1967), although as late as 1937 arguments were reviewed for a theory of magnetic storms and aurora in which the driving solar emission was ultraviolet light (Hulbert, 1937; cf., Chapman and Bartels, 1940).

One final puzzle piece needed to be uncovered, however, before the 1859 event could be explained in its entirety. The Carrington flare had been accompanied by a simultaneous deflection of Earth's magnets as well as by the geomagnetic storm 17.6 h later (Fig. 4). The fact that two magnetic effects were observed was a source of confusion. Did the flare cause the prompt effect, the delayed effect (storm), or both? The magnetic crochet that accompanied the 1859 flare, a relatively small effect in comparison with the storm activity, was dismissed by some (e.g., Ellis, 1893) as a chance alignment. The needed breakthrough in understanding was provided by Dellinger (1935, 1936, 1937) and others who discovered that short wave fadeouts on radio communication links occurred coincidentally with flares. From this, Dellinger inferred the existence of highly penetrating "ultravisible" solar flare radiation that increased ionization and radio wave absorption in the lower regions of the Earth's ionosphere.

Within two years of the initial report by Dellinger (Fig. 6(b)), Julius Bartels (Fig. 6(c)), Director of the Potsdam Magnetic Observatory and a research associate at the Department of Terrestrial Magnetism at the Carnegie Institution, provided a complete description of the Carrington event. Bartels (1937) linked the magnetic crochet associated with the 1859 flare to Dellinger's newly discovered ionizing radiation and following Hale and Chapman attributed the ensuing great storm to the impact of solar corpuscles [in today's terminology, a coronal mass ejection (CME)]. After nearly 80 years, the correct interpretation had been provided for the Carrington event.

By 1943, enough evidence ("swallows") had been accumulated to enable H.W. Newton, successor of Maunder as a solar expert at the Royal Greenwich Observatory, to provide statistical evidence for an association between large solar flares and magnetic storms. From the central disk positions of flares associated with great geomagnetic storms, Newton (1943) was able to make an inference about the size of the then as yet undiscovered CMEs. For the major solar events in his sample, Newton obtained an angular width for the ejected corpuscular stream of ~90° that is consistent with current determinations of the angular spans of the largest limb CMEs (Burkepile et al., 2004). The median Sun-storm delay time of 25 h (range from 17.5 to 38 h) Newton deduced for 11 great storms (defined as those having lower limit deflections of 60′ in declination or 300 nT in the horizontal or vertical components of the field) with high-confidence flare associations between 1859 and 1942, compares with a median delay of 31.3 h (range from 14.6 to 54.8 h) obtained by Cliver et al. (1990) for 23 large ($Ap^* \geqslant 100$) magnetic storms with unambiguous sources occurring from 1938 to 1989.

6. Fast forward to the present

6.1. New windows opened for flare observation during the mid-20th century

During the 1940s, the radio (Appleton and Hey, 1946) and energetic particle emissions (Forbush, 1946) associated with flares were observed for the first time, and the period from 1956 to 1960 witnessed the advent

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[15] Hale referred to flares as solar eruptions. To the best of my knowledge (Cliver, 1995b), the term "flare" was first mentioned in Bartels (1932) paper and was first used in the title of a paper by Newton (1943).

of flare X-ray observation (Kreplin et al., 1962) with space borne detectors. Recently, quantitative estimates have been made for both the soft X-ray and solar energetic proton (SEP) output of the 1859 event. Cliver and Svalgaard (2004) used the amplitude of the SFE associated with the Carrington flare to infer a peak flare soft X-ray class of >X10 (intensity $>10^{-3}$ W m^{-2}), placing it conservatively within the largest 100 flares of the past ~150 years. McCracken et al. (2001) used nitrate composition in ice cores to deduce a >30 MeV proton fluence of $\sim 20 \times 10^9$ pr cm^{-2}, approximately twice as large as any event since 1560.[16]

6.2. The ongoing search for geomagnetic storm drivers

In some sense, the history of solar terrestrial-physics can be described in terms of the successive replacement/refinement of the solar drivers of geomagnetic storms (see Cliver, 1994a,b, 1995a). In the beginning were sunspots. These were replaced by M-regions and flares which were replaced in turn by coronal holes (Krieger et al., 1973; Neupert and Pizzo, 1974) and coronal mass ejections (Gosling et al., 1991), respectively. In a "post modern" view of M-regions, Crooker and Cliver (1994) emphasized the importance of interaction regions between fast and slow solar wind streams for geomagnetic activity, thus expanding the view of M-regions to include streamers as well as adjacent coronal holes. Following Gosling et al. (1991) and Richardson et al. (2001), it is recognized that the largest geomagnetic storms have their origins in coronal mass ejections, but much remains to be done. The relationship of CMEs to flares remains a matter of controversy (e.g., Gosling, 1993; Švestka, 1995; Zhang et al., 2001; Cliver and Hudson, 2002) and the nature of underlying "magnetic disease" (Harrison, 1995) responsible for both phenomena remains unspecified.

7. Conclusion

The story of the 1859 event underscores the importance of new observations.[17] It took nearly 80 years for Bartels, building on the work of others, to be able to provide a complete description of the relationship of the solar observations made by Carrington and Hodgson to the prompt and delayed disturbances of the magnetic records from Kew. However, Bartels' complete description came only two years after the last puzzle piece – solar flare ionizing radiation inferred from the observation of short wave fades – became known. Also, less than a decade passed between Hale's establishment of the world wide flare patrol and the forging of a statistical link between solar eruptions and geomagnetic storms.

In our own time, the discovery of coronal holes by soft X-ray and EUV detectors in space was almost immediately followed by their identification with the elusive M-regions as the source of recurrent storms. The ~20-year delay between the discovery of CMEs (Koomen et al., 1974, and references therein) and the general recognition that CMEs were the proximate cause of large nonrecurrent storms was due at least in part to the difficulty of identifying reliable signatures of CMEs in the interplanetary medium (e.g., Zwickl et al., 1983). As the following papers in this issue show new knowledge and techniques acquired during the space and computer age enable us to look at the Carrington event with fresh eyes and gain a depth of understanding that was denied our predecessors. The hope is that future scientists will derive similar pleasure in addressing the questions that surpass us.

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[16] The ice cores are sampled about 20 times per year; the detailed record for the 1859 event (McCracken et al., 2001) shows onset near the beginning of September. The time resolution of the measurements makes it impossible to separate the relative SEP contributions of the solar disturbances responsible for the 28 August and 2 September magnetic storms, but the finding by Shea and Smart (1990) that the highest fluence SEP events tend to be associated with central meridian flares (Shea and Smart, 1994) is consistent with a dominant role for the 1 September eruption.

[17] Even when theory played a leading role as with Parker's (1958) prediction of a continuous solar wind (a culmination of the corpuscular hypothesis), the issues and debates (e.g., the Chapman/Biermann dilemma and the solar wind/breeze controversy (see reviews by Parker, 1965, and Dessler, 1965) were ultimately settled by observation.

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