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## THE 1859 SOLAR–TERRESTRIAL DISTURBANCE AND THE CURRENT LIMITS OF EXTREME SPACE WEATHER ACTIVITY

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**Abstract.** It is generally appreciated that the September 1859 solar–terrestrial disturbance, the first recognized space weather event, was exceptionally large. How large and how exceptional? To answer these questions, we compiled rank order lists of the various measures of solar-induced disturbance for events from 1859 to the present. The parameters considered included: magnetic crochet amplitude, solar energetic proton fluence (McCracken *et al.*, 2001a), Sun–Earth disturbance transit time, geomagnetic storm intensity, and low-latitude auroral extent. While the 1859 event has close rivals or superiors in each of the above categories of space weather activity, it is the only documented event of the last ~150 years that appears at or near the top of all of the lists. Taken together, the top-ranking events in each of the disturbance categories comprise a set of benchmarks for extreme space weather activity.

### 1. Introduction

The study of space climate involves both long-term average behavior and variations about those long-term averages. Here we consider extreme deviations from the norm, centering our analysis on the great solar-terrestrial event of 1859.

Increasing worldwide concern with space weather has rekindled interest in the September 1859 magnetic storm. This storm is notable both for its association with the first solar flare ever reported (observed in white light by Carrington (1860) and Hodgson (1860); see Cliver (2004) for a historical review) and for its size. The severity of the 1859 event was appreciated from the outset (Loomis, 1859; Stewart, 1861) and recent analyses (McCracken *et al.*, 2001a; Tsurutani *et al.*, 2003) have only enhanced its stature. In this study, we take a synoptic view of the September 1859 solar–terrestrial event and compare its various effects (from sudden ionospheric disturbance through aurora) with those of other great solar-induced disturbances observed during the intervening ~150 years. Where does the 1859 event rank in comparison with other large disturbances for these effects? Was, by remarkable coincidence, the first space weather event also the biggest? What are the current “worst case” examples/limits for the various categories of space weather? In Section 2, we address these questions by compiling rank order lists

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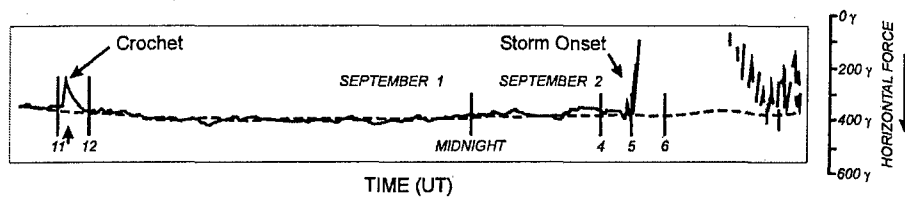


Figure 1. Trace of the horizontal component of Earth's magnetic field from Kew Observatory for 1–2 September 1859, showing the magnetic crochet at 11:15 UT on 1 September and the great geomagnetic storm that followed 17.6 h later and drove the record off scale (Stewart, 1861; Bartels, 1937).

of space weather effects for events from 1859 to the present and in Section 3 we discuss our results.

## 2. Data Compilation

### 2.1. SUDDEN IONOSPHERIC DISTURBANCE: SOLAR FLARE EFFECT

The solar flare effect (SFE; also called magnetic crochet) is a type of sudden ionospheric disturbance caused by a soft X-ray/EUV-driven enhancement of the ionospheric current vortices responsible for the regular daily variation observed on magnetometer traces (see Nagata, 1966; Richmond and Venkateswaran, 1971, for reviews). To first order, SFE intensity varies inversely with the solar zenith angle, but there is a local minimum at the center of the vortex in each hemisphere.

The magnetic crochet recorded on the magnetic traces at Kew Observatory on 1 September 1859 (indicated by an arrow in Figure 1) in conjunction with the white-light flare (hereafter referred to as the Carrington flare) provided the first indication of a solar-terrestrial connection for discrete solar events and the first evidence of solar flare-ionizing radiation. As reviewed in Cliver (2004), nearly 80 years would pass before the implications of the simultaneous occurrence of the flare and the SFE were grasped.

To 19th century geomagneticians (e.g., Ellis, 1893) the feature noted by both Carrington and Hodgson in the Kew records at 11:15 UT appeared to be an unremarkable disturbance; for example, it was dwarfed by the storm that followed  $\sim 18$  h later. In fact, however, the  $\sim 110$  nT  $H$ -component amplitude (Bartels, 1937; Newton, 1943) of the crochet places it among the largest mid-latitude SFEs ever reported.<sup>1</sup> A scan of the literature (Newton, 1949; McIntosh, 1951; Nagata, 1966; Ellison, McKenna, and Reid, 1961; Richmond and Venkateswaran, 1971) for the period from 1936–1968, spanning the time from the recognition of sudden ionospheric

<sup>1</sup>There are reported SFEs from equatorial stations (Michie Smith, 1910; Torreson, Scott, and Stanton, 1936; Rastogi *et al.*, 1997) with amplitudes  $> 100$  nT that are not included in Table I; such events are strongly enhanced by the equatorial electrojet and cannot be directly compared with those at higher latitudes. We did not consider high-latitude (auroral zone or above) regions in our search for large SFEs.

disturbances (Dellinger, 1937) to the onset of direct observations of flare X-ray emissions via satellites, reveals only one event with a larger amplitude. The flare on 28 February 1942, associated with the first reported solar "cosmic ray" (>500 MeV proton) event (Forbush, 1946), had an SFE  $H$ -component amplitude of 112 nT at Eskdalemuir (McIntosh, 1951; 69 nT at Abinger, Newton, 1949).

To estimate the size of the Carrington flare and gauge the maximum size of SFEs, we compiled a list of intense (>X10; strictly  $\geq$ X11) 1–8 Å soft X-ray flares from 1984–2003 and searched the available (<http://spidr.ngdc.noaa.gov/spidr>; <http://www.intermagnet.org>) geomagnetic data for stations covering a broad range ( $\sim 20$ – $80^\circ$ ) of solar zenith angles for associated crochets. During this interval, 14 > X10 flares were observed. For at least three cases (16 August 1989, 1 June 1991, and 11 June 1991), geomagnetic activity not necessarily due to the solar flare effect could have masked a crochet, masqueraded as one, or added to its amplitude. We eliminated these events from further consideration. For the 11 remaining events, there were two cases (Figure 2) of SFEs with amplitudes >100 nT; smaller SFEs were found in all other cases. The maximum SFE for the 4 November 2003 event (decrease in the  $H$ -component, Figure 2b) was observed at Newport, Washington

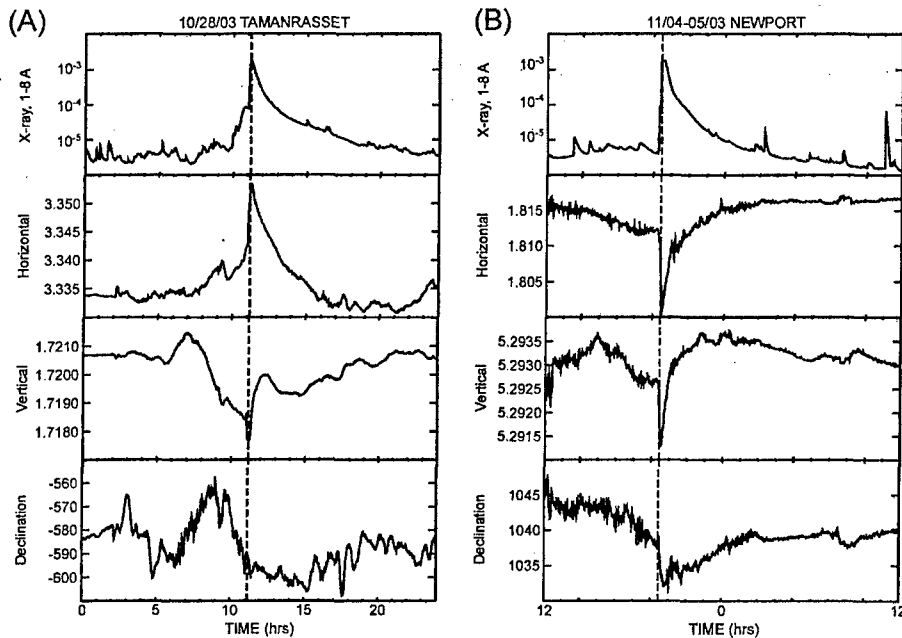


Figure 2. Large (>100 nT) SFEs on (a) 28 October 2003 and (b) 4 November 2003. In each case the associated soft X-ray burst is shown along with the magnetometer traces of the station showing the largest  $H$ -component deflection. The vertical dashed lines are drawn at the peak of the soft X-ray event. The units for the soft X-ray fluxes in the top panels of (a) and (b) are  $\text{watt m}^{-2}$ . In the second and third panels of both (A) and (B), the plotted values should be multiplied by  $10^4$  (units are nT); in the bottom panel of each figure, the plotted values should be multiplied by 10 (units are arcmin).

TABLE I

Outstanding solar flare effects at mid-latitudes identified in a literature search for events from 1936–1968 and from associations with >X10 soft X-ray flares, 1984–2003.

Date	1–8 Å Class	Magnetometer station	Zenith angle (°)	SFE amplitude (nT)
04 Nov. 2003	X28	Newport	63	115
28 Feb. 1942	–	Eskdalemuir	63	112
28 Oct. 2003	>X17	Tamanrasset	36	111
01 Sep. 1859	–	Greenwich	44	110
15 Jun. 1991	>X12	Hyderabad	22	95
06 Jun. 1991	>X12	Guam	20	90
15 Apr. 2001	>X15	Tamanrasset	34	85

(zenith angle = 63°). This situation is similar to that for the 1859 case where both Greenwich and Kew had relatively large zenith angles (44°) and to that for 28 February 1942 for which the zenith angle at Eskdalemuir was 63°. A list of the largest mid-latitude SFEs uncovered in our literature search and from examination of geomagnetic traces at the times of large flares is given in Table I.

We emphasize that measuring the amplitudes of SFEs can be a subjective exercise involving separation of other types of geomagnetic activity from the SFE to determine the event onset time. Moreover, the measured amplitude of an SFE is strongly dependent on the placement of observing stations relative to the subsolar point and the ionospheric current vortex. The larger the number of well-placed magnetometers for a given event, the greater the likelihood that the true maximum amplitude will be observed. For example, the data available on the web for the 15 June 1991 event only included stations with zenith angles ranging from 38–90°; the largest SFE for this station set was ~45 nT. However, Rastogi *et al.* (1997) published separately the data from the well-placed Indian chain of magnetometers showing an SFE with an *H*-component deviation of 95 nT at Hyderabad (~8°N geomagnetic latitude and a zenith angle of 22° at the time of the flare). In this regard, it is remarkable that the 1 September 1859 SFE which was only recorded at Kew and Greenwich near London had such a large amplitude.

Because our search revealed no SFEs with amplitudes significantly greater than that for the 1 September 1859 flare (Table I), we conservatively conclude that the Carrington flare was a >X10 soft X-ray event, placing it among the top ~100 ((14 events/20 years) × 145 years) flares of the last ~150 years. Considering that the other events in Table I include four solar cosmic ray flares (28 February 1942, 15 June 1991, 15 April 2001, and 28 October 2003; R. Pyle, personal communication, 2004), two “fast transit” solar wind disturbances (28 February 1942 and 28 October 2003, see Section 2.3), and the largest flare recorded by the GOES soft X-ray detector (X28 on 4 November 2003 (*Boulder Preliminary*

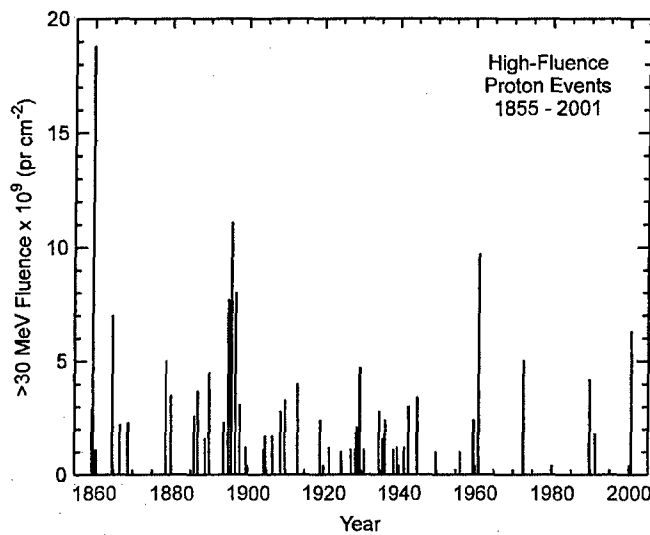


Figure 3. The times of occurrence of all  $>30$  MeV proton events with fluences exceeding  $10^9$   $\text{pr cm}^{-2}$  between 1855–2000 (adapted from McCracken *et al.*, 2001a; M. Shea, personal communication, 2004). Pre-1950 values are based on nitrate composition in ice cores and later values are based on ionospheric measurements and direct satellite observations.

Report)), it seems likely that the Carrington event would rank high among these 100 flares.<sup>2</sup>

## 2.2. SOLAR ENERGETIC PROTONS

McCracken *et al.* (2001a,b) have used nitrate composition in ice cores to obtain a list of large solar energetic proton (SEP) events occurring from 1561–1950; they extended the list to the year 1994 by using ionospheric and satellite data. Figure 3 adapted from McCracken *et al.* (2001a), shows the times of occurrence of all  $>30$  MeV proton events with fluences exceeding  $10^9$   $\text{pr cm}^{-2}$  between 1855–2000 (update through 2000 based on M. Shea, personal communication, 2004). A list of the nine largest  $>30$  MeV fluence events during this interval is given in Table II where it can be seen that the 1859 event is a factor of 1.7 (possibly a factor of 3.4, McCracken *et al.* (2001b)) larger than second ranked event. It is important to note that the listed

<sup>2</sup>The white-light observations also permit an estimate of the size of the September 1859 flare. Don Neidig (in Tsurutani *et al.*, 2003) estimated a total output in white light of  $\sim 2 \times 10^{30}$  ergs. This compares with an estimate of  $\sim 6 \times 10^{30}$  ergs for the  $>X13$  flare on 24 April 1984, the peak white-light output for any event computed to date. The  $\sim 6 \times 10^{30}$  ergs estimate for the April 1984 flare represents a downward adjustment by a factor of 10 from that reported by Neidig, Grosser, and Hrovat (1994), the result of taking differences in observing technique for the 1859 and 1984 events into account (D. Neidig; personal communication, 2004). Specifically, the area of the 1984 event was decreased to match what Carrington could have been expected to see on a projection board. The estimate for the 1984 flare is uncertain by a factor of 2–3 and the uncertainty for the Carrington event is larger.

TABLE II  
Large solar energetic proton events, 1859–2000<sup>a</sup>.

Date <sup>b</sup>	>30 MeV SEP fluence (10 <sup>9</sup> pr cm <sup>-2</sup> )
Aug.–Sep. 1859	18.8
1895	11.1
Nov. 1960	9.7
1896	8.0
1894	7.7
1864	7.0
Jul. 2000	6.3
1878	5.0
Aug. 1972	~5

<sup>a</sup>McCracken *et al.*, 2001a; see text for sources of data.

<sup>b</sup>Only year given for events without identified candidate sources.

events in 1960 and 1972 involved multiple eruptive flares (Švestka and Simon, 1975; Coffey, 1973; McCracken *et al.*, 2001a). The great geomagnetic storm beginning on 2 September 1859 (Figure 1) was preceded by a major storm on 28 August (Stewart, 1861; Loomis, 1859; Cliver, 2004). It is likely that the solar eruption responsible for the August storm contributed to the proton fluence listed in Table II.

### 2.3. SUN–EARTH TRANSIT TIME

Cliver, Feynman, and Garrett (1990a,b) compiled a list of 10 “fast transit” events occurring from 1859–1989 in which a solar flare was followed within ~20 h by the sudden commencement of a geomagnetic storm. Table III is an update of their list through 2003. The shortest transit time (measured from inferred/observed flare onset to geomagnetic storm sudden commencement) for the listed events is 14.6 h for the 4 August 1972 flare-storm pair. The 1859 event had the second shortest delay, 17.6 h. On average, fast transit events appear to occur 1–2 times per solar cycle, but the temporal distribution is very uneven, with 6 such events occurring from 1938–1946 and a 31-year gap between the 4 August 1972 and 28 October 2003 events followed by a one day gap between the two October 2003 events. Solar wind measurements for the three modern events on the list (4 August 1972 (Vaisberg and Zastenker, 1976; d’Uston *et al.*, 1977) and 28 and 29 October 2003 (Skoug *et al.*, 2004)) indicate peak speeds ~ 2000 km s<sup>-1</sup>.

### 2.4. GEOMAGNETIC STORM

The great geomagnetic storm beginning on 2 September 1859 has recently attracted renewed attention. Tsurutani *et al.* (2003) reanalyzed the Colaba (Bombay/Mumbai)

TABLE III  
 "Fast-transit" events, 1859–2003.

Flare date	Transit time (h)	References
04 Aug. 1972	14.6	1, 2, 3
01 Sep. 1859	17.6	4, 5, 6, 7, 8
06 Feb. 1946	17.8	3, 9
28 Feb. 1941	18.4	10
16 Jul. 1959	19.4	11
28 Feb. 1942	19.5	8, 12
17 Sep. 1941	19.8	8, 13
29 Oct. 2003	~20 <sup>a</sup>	14
28 Oct. 2003	20.3 <sup>a</sup>	14
15 Apr. 1938	21.2	8, 15
12 Nov. 1960	21.2	11
16 Jan. 1938	21.8	15, 16

References: (1) Dryer *et al.*, 1975; (2) Vaisberg and Zastenker, 1976; (3) Cliver *et al.*, 1990b; (4) Carrington, 1860; (5) Hodgson, 1860; (6) Hale, 1931; (7) Bartels, 1937; (8) Newton, 1943; (9) Nicholson and Hickox, 1946; (10) Newton, 1941a; (11) Ellison, McKenna, and Reid, 1961; (12) Newton, 1942; (13) Newton, 1941b; (14) Skoug *et al.*, 2004; (15) Bartels, 1940; (16) Bartels, Heck, and Johnston, 1939.

<sup>a</sup>Preliminary.

Observatory horizontal intensity record for this event and found it to be consistent with a *Dst* index of  $-1760$  nT, calculated from estimated solar wind parameters. This peak value is approximately three times that of the 13 March 1989 storm. The March 1989 event is the largest storm since 1957, the first year for which the *Dst* index was computed. In fact on the basis of a recent extension/recomputation of the *Dst* index (Karinen and Mursula, 2004), we can say that the March 1989 storm had the largest peak *Dst* value of any storm since 1932, the year with which Karinen and Mursula begin their series. Siscoe (2004) attempted to model the Colaba horizontal trace for the September 1859 storm and were unable to fit the intense decrease and sharp recovery (see also Li *et al.*, 2004).

Questions about the reconstruction/interpretation of the Colaba record also arise from a comparison of the 1859 event with subsequent great storms. Unfortunately, the longest running standard index of geomagnetic activity, the Mayaud *aa* index (Mayaud, 1972, 1980), is only available from 1868. Thus it is not possible to directly compare the 1859 storm with subsequent severe activity. The problem is exacerbated by the fact that the magnetic traces went off scale at Greenwich and Kew, the two stations besides Colaba with continuous recording during the event. We note that while Chapman and Bartels (1940) included the 1859 event in a list



TABLE IV

Chronological listing of outstanding geomagnetic storms recorded at Greenwich/Abinger, 1859–1954<sup>a</sup>.

Date	Ranges		
	Declination (°)	Horizontal force (nT)	Vertical (nT)
01 Sep. 1859	≫92	≫625	1500
04 Feb. 1872	125	800	>950
17 Nov. 1882	115	>1090	>1060
31 Oct. 1903	119	1175	1440
25 Sep. 1909	193	1710	>1080
14 May 1921	110	≫740	≫460
25 Jan. 1938 <sup>b</sup>	126	1055	570
16 Apr. 1938	307	1375	500
24 Mar. 1940	131	1370	1000
01 Mar. 1941	186	1650	1310
18 Sep. 1941	123	1250	1115
28 Mar. 1946	162	1660	920
21 Sep. 1946	136	925	450

<sup>a</sup>Jones, 1955.

<sup>b</sup>This storm was not included in Chapman and Bartels' (1940) list of great storms from 1857–1939.

of seven storms that they characterized as “the most violent since 1857” in their classic book *Geomagnetism*, they did not single it out for its size.<sup>3</sup> The seven events listed by Chapman and Bartels (some of which are compound storms) are included in a longer list extending to 1954 of outstanding storms at Greenwich (Jones, 1955), reproduced here as Table IV. The Z range of 1500 nT for the 1859 event (the only component which did not go off scale) is not markedly larger than that observed for listed storms in 1903 and 1941.

Allen (1982) devised the  $Ap^*$  index, defined to be the peak value of the running 24-h mean of 3-h  $ap$  values during a storm, to give a measure of a storm weighted toward long duration at high intensity. Recently Svalgaard, Cliver, and Ling (2002) have devised a new index called  $aa_m$  that is based on the  $aa$  index but which has the universal time variation of the  $am$  index (Mayaud, 1980). This permits the construction (following Allen's procedure for  $Ap^*$ ) of a list of outstanding  $Aa_m^*$  storms for the period from 1868–1998 (at present only preliminary  $aa$  data

<sup>3</sup>Stewart (1861; repeated in Chapman and Bartels, 1940) reported that Sabine “in his long and varied experience” found that the “great magnetic storm (the combined storms beginning on 28 August and 2 September). . . for excessive violence of character and length of duration has never been surpassed by any similar phenomenon.”

are available after 1998; the largest post-1998 storms include 16 July 2000, 31 March 2001, 30 October 2003, and 20 November 2003). A correction based on the non-constant calibration of the  $aa$  index from 1868 – present (Svalgaard, Cliver, and Le Sager, 2004) is then applied to the peak  $Aa_m^*$  values to yield the rank-ordered list of the 25 largest  $Aa_m^*$  storms in Table V. Comparison of the lists in Tables IV and V reveals that the six post-1867 storms listed by Chapman and Bartels, which (presumably) included the Carrington storm as a peer, are surpassed by, and intermingled with, the more recent events, suggesting that the Carrington storm ranks among, but not significantly beyond, the greatest storms observed in

TABLE V

The 25 largest geomagnetic storms based on the  $Aa_m^*$  index, 1868–1998.

Date	Time (UT h) <sup>a</sup>	Peak value (nT)
18 Sep. 1941	10	425
14 May 1921	13	417
13 Mar. 1989	07	402
17 Nov. 1882	10	399
24 Mar. 1940	16	378
31 Oct. 1903	07	361
07 Jul. 1928	22	347
25 Sep. 1909	07	341
12 Nov. 1960	19	338
19 Nov. 1882	22	332
16 Apr. 1882	22	328
28 Mar. 1946	04	322
15 Jul. 1959	07	305
22 Sep. 1946	04	291
13 Feb. 1892	07	289
31 Mar. 1960	22	285
05 Jul. 1941	01	285
04 Aug. 1972	19	280
04 Feb. 1872	10	278
11 Feb. 1958	01	276
25 May 1967	13	274
08 Jul. 1958	07	273
22 Mar. 1920	13	260
08 Feb. 1986	07	259
07 Feb. 1946	10	254

<sup>a</sup>The time corresponds to the start of the 24-h period used to define  $Aa_m^*$ .

the intervening  $\sim 150$  years. We note that the great low-latitude auroral storm of 4 February 1872 (see Section 2.5) ranks 19th of the 25 storms in Table V.

The top 25  $Dst$  storms from 1932–2002 based on the reconstructed index of Karinen and Mursula (2004) index are given in Table VI. In Figure 4, we compare peak  $Dst$  vs.  $Aa_m^*$  for storms from 1932–1998. To compare storms measured in these two indices, we used the peak hourly  $Dst$  value measured during a 48-h interval encompassing the 24-h period used to derive  $Aa_m^*$  and 12 h on either side of it. The plot includes all  $Dst$  storms with peak values  $\leq -150$  nT and all storms with  $Aa_m^*$  values  $\geq 100$  nT. In general, the correspondence in Figure 4 is quite good, although there are outliers such as the intense short-lived storm on 13 September 1957

TABLE VI

The 25 largest geomagnetic storms based on the  $Dst$  index, 1932–2002<sup>a</sup>.

Date	Time (UT h)	Peak value (nT)
14 Mar. 1989	01	-548
05 Jul. 1941	13	-453
28 Mar. 1946	14	-440
15 Jul. 1959	19	-434
11 Feb. 1958	11	-428
13 Sep. 1957	10	-426
26 May 1967	04	-391
31 Mar. 2001	08	-383
01 Mar. 1941	18	-382
09 Nov. 1991	01	-375
24 Mar. 1940	20	-366
19 Sep. 1941	06	-359
25 Jan. 1938	23	-352
26 Jan. 1949	00	-350
22 Jan. 1938	11	-344
08 Jul. 1958	20	-334
13 Nov. 1960	09	-333
30 Apr. 1960	18	-325
01 Apr. 1960	18	-325
05 Sep. 1957	03	-324
14 Jul. 1982	03	-322
04 Sep. 1958	22	-305
23 Sep. 1957	07	-302
16 Jul. 2000	00	-301
25 Mar. 1991	00	-297

<sup>a</sup>Based on  $Dst$  index from Karinen and Mursula, 2004.

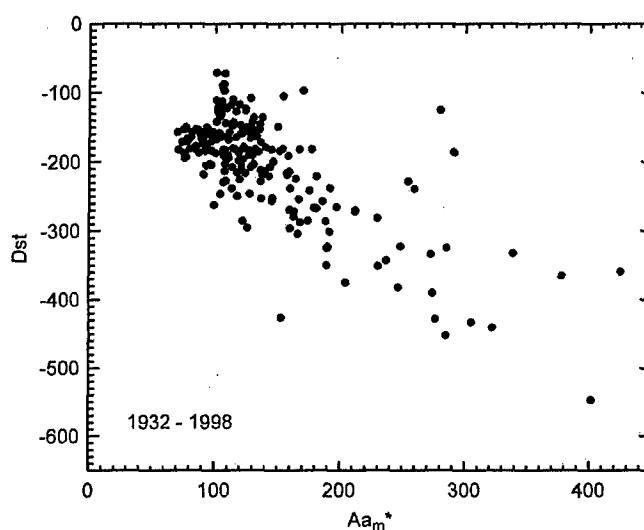


Figure 4. A comparison of peak  $Dst$  vs.  $Aa_m^*$  values for large geomagnetic storms from 1932–1998.

(153,  $-426$ ) and the 4 August 1972 (280,  $-125$ ) event for which incomplete solar wind data show principally northward magnetic field (Lanzerotti, 1992). Since the two indices have different dependencies on solar wind parameters (e.g., Feynman, 1980), some scatter is expected. The 13 March 1989 storm is the only event in the last  $\sim 70$  years with both a peak  $Dst$  value  $< -500$  nT ( $-547$ ) and a peak  $Aa_m^*$  value  $> 400$  nT (402). Since 1932, no storm has occurred with a peak  $Dst$  index within  $\sim 1000$  nT of the  $-1760$  nT value deduced by Tsurutani *et al.* for the 1859 storm. Assuming that the correlation between peak  $Dst$  and  $Aa_m^*$  holds for earlier periods, we can use Table V to infer the absence of such a storm back to 1868 (see Willis, Stevens, and Crothers, 1997).

## 2.5. AURORA

Only six well-documented auroras (Table VII) observed within  $30^\circ$  of the geomagnetic equator were reported between 1859 and the International Geophysical Year (IGY) of 1957–1958 (Botley, 1957; Chapman, 1957a; Adem, 1958; Vallance Jones, 1992; S. Silverman, personal communication, 2004).<sup>4</sup> The 2 September 1859 storm was observed as far north as Santiago and Valparaiso, Chile (magnetic latitude =  $22^\circ$ ) in the southern hemisphere and as far south as San Salvador, El Salvador ( $24^\circ$ ) and Honolulu, Hawaii ( $20^\circ$ ) in the northern hemisphere (Loomis, 1859, 1860a,b, 1861; Kimball, 1960). Auroral sightings at the peak of this storm

<sup>4</sup>An aurora on 28 August 1859 that was observed within  $32^\circ$  of the geomagnetic equator was presumably associated with the same active region as the 2 September event, indicating a source for the August storm well-removed ( $\sim E60$ ) from central meridian (Cliver, 2004).

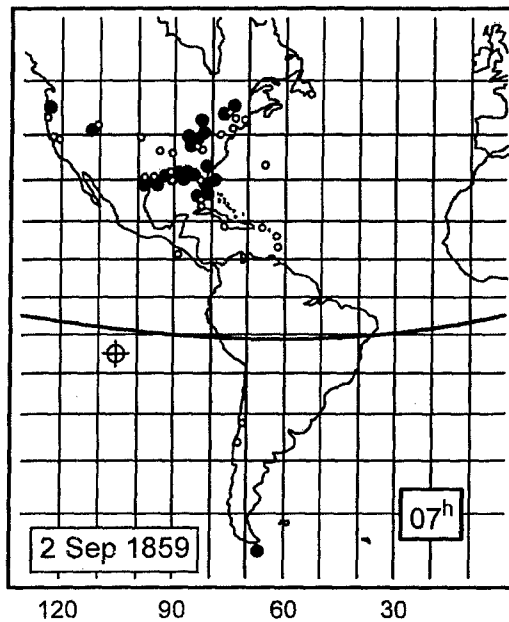


Figure 5. Auroral sightings at the peak ( $\sim 07$  UT on 2 September) of the 1859 storm (adapted from Kimball, 1960) for the American sector. *Closed circles* represent overhead aurora; *open circles* represent visible aurora. The *heavy curved line* denotes the geomagnetic equator and the  $\oplus$  symbol indicates the anti-Sun point. The lowest geomagnetic latitude at which the storm was observed was Honolulu ( $20^\circ$ ; not shown).

are given in Figure 5 (adapted from Kimball, 1960). Of the five aurora in Table VII, two had well-documented reports of equatorward extensions that exceeded the  $20^\circ$  (Honolulu) low latitude extreme of the September 1859 storm.<sup>5</sup> Silverman and Cliver (2001) re-examined the report of an aurora at Apia, Samoa ( $13^\circ$ S geomagnetic) in May 1921 and concluded that the report was credible, although puzzling because it implied an auroral height of  $\sim 2000$  km (assuming overhead aurora at Auckland). Reports of aurora at Bombay ( $10^\circ$ N) and Aden ( $8^\circ$ N) for the February 1872 storm were reviewed by Chapman (1957b) and are currently under reexamination by Silverman and Cliver. In this case, however, there are several observations of aurora within  $19$ – $24^\circ$  of the geomagnetic equator (Chapman, 1957b), so there is no question that this event was at least comparable to the September 1859 aurora. Botley (1959) judged the 1872 aurora to be the greatest of the modern epoch, surpassing that of 1859, and Chapman (1968) described it as “what seems to me to be the most remarkable aurora amply and reliably recorded up to the present time.” In sum, during a 100-year period, at least one aurora, on 4 February 1872, was

<sup>5</sup>Aurora was reported at Singapore (magnetic latitude  $8^\circ$ S) for the September 1909 storm, but Silverman (1995) has shown that this was likely the result of confusion on the part of a reporter between actual aurora and the effects of the geomagnetic activity on telegraphy.

TABLE VII  
Low-latitude auroras, 1859–1958<sup>a</sup>.

Date	Low-latitude extent	Reference
4 Feb. 1872 <sup>b</sup>	19°	Chapman (1957a,b)
2 Sep. 1859	20°	Loomis (1859, 1860a,b, 1861); Kimball (1960)
11 Feb. 1958	28°	Adem (1958)
14 May. 1921	30° (see text)	Silverman and Cliver (2001)
25 Sep. 1909	30°	Silverman (1995)
25 Jan. 1938	30°	S. Silverman (personal communication, 2004)

<sup>a</sup>To these we can add the 13 March 1989 event (29°N), the only aurora we are aware of that was observed within 30° of the geomagnetic equator since 1958. No systematic search has been made, however, so we restrict the listed events to the time period indicated. Even for the 1859–1958 interval, there is the possibility that other such events exist (Chapman, 1957a).

<sup>b</sup>Reports of aurora at lower latitudes (e.g., at Bombay at 10°N geomagnetic latitude) for this event are currently under investigation.

observed that matched the September 1859 event in its low latitude extent and it is possible that both the 1872 and 1921 auroras approached closer to the geomagnetic equator than the 1859 event. Since the IGY, the lowest latitude aurora that we are aware of (no systematic search has been made) was that accompanying the great March 1989 storm. It was observed at 29°N geomagnetic latitude (S. Silverman, personal communication, 2004).

## 2.6. CURRENT STANDARDS FOR EXTREME SPACE WEATHER ACTIVITY

For the various aspects of space weather activity considered in Sections 2.1–2.5, the current defining levels/ranges for extreme variation, culled from the compiled lists, are presented in Table VIII.

## 3. Discussion

In this study we used the great solar-terrestrial disturbance of 1859 as a point of departure for an investigation of the limits of extreme space weather activity. We considered the various aspects of space weather disturbance: sudden ionospheric disturbance, solar energetic particles, solar wind, geomagnetic storm, and aurora. For each of these effects, we compiled (with varying degrees of completeness) size-ordered lists of the top events of the last ~150 years. We found that in each of these categories the 1859 event had close peers or superiors. It appears to have been the largest event only in terms of solar energetic proton fluence where it was a factor of ~2 larger than an event in 1895 (McCracken *et al.*, 2001a). Various lines of evidence indicate that the intensity of the geomagnetic storm beginning on 2

TABLE VIII  
Current extreme values for various space weather activity parameters.

Space weather effect	Parameter	Value	Event date	References
Sudden ionospheric disturbance	Magnetic crochet amplitude	115 nT	04 Nov. 2003	(1)
Solar energetic particles	>30 MeV proton fluence	$18.8 \times 10^9$ pr cm <sup>-2</sup>	Aug.–Sep. 1859	(2)
Solar wind	Sun–Earth transit time	14.6 h	04 Aug. 1972	(3)
Geomagnetic storm	Peak/average intensity	$Dst$ , –548 nT/ $Aa_m^*$ , 425 nT	14 Mar. 1989/ 18 Sep. 1941	(1)
Aurora	Low-latitude extent	19 <sup>o</sup> <sup>a</sup>	04 Feb. 1872	(4)

<sup>a</sup>Reports of lower latitude sightings (at  $\sim 10^\circ\text{N}$ ) for the 1872 aurora are currently under investigation. See text for discussion of the September 1909 (Silverman, 1995) and May 1921 (Silverman and Cliver, 2001) auroras reported at  $8^\circ\text{S}$  and  $13^\circ\text{S}$ , respectively.

References: (1) this paper; (2) McCracken *et al.* (2001a,b); (3) Cliver *et al.*, 1990b; (4) Chapman (1957a,b).

September 1859 was not markedly larger (if it was larger at all) than that of the top tier of subsequent great storms, contrary to the findings of Tsurutani *et al.* (2003).

At the same time, the 1859 space weather event stands alone as the single event that appears on all of the effect lists (taking into account that flare data, and as a result transit time data, are unavailable for many of the early events). For example, the great auroras in February 1872, September 1909, and May 1921 were not accompanied by outstanding >30 MeV proton events (assuming the validity/fidelity of ice core measures for these years) while the great storm and fast-transit event of September 1941 apparently lacked both a low-latitude aurora and a strong particle event. After  $\sim 150$  years, the first identified space weather event continues to be one of the largest ever recorded – across the activity spectrum.

Our focus has been on the interplanetary and terrestrial aspects of the 1859 event. In closing, it is useful to remember that significantly larger solar active regions have been observed than the large and complex region (sunspot area  $\sim 2300$  millionths of a hemisphere; Newton, 1943) in which the 1 September 1859 flare originated. Regions with spot areas  $\sim 5000$  millionths appeared during cycle 18 (Newton, 1955). Although the correlation between active region size and terrestrial event intensity is rather loose (e.g., Cliver and Crooker, 1993), the presence of a major spot group certainly increases the probability of occurrence of strong activity. For example, the largest solar active region during the space age (NOAA/SEC Region 5395; 3500 millionths of a hemisphere) is linked to the notable space weather event of March 1989 (Allen *et al.*, 1989). Thus we should not be surprised if/when the space weather effects of future events exceed any or all of the current standards in Table VIII.

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