AGU100 ADVANCING EARTH AND SPACE SCIENCE

JGR Space Physics

RESEARCH ARTICLE
10.1029/2019JA027336

Magnetic Field Measurements From Rome During the August–September 1859 Storms

Seán P. Blake[1,2], Antti Pulkkinen[2], Peter W. Schuck[2], Heikki Nevanlinna[3], Oreste Reale[4,5], Bhaskara Veenadhari[6], and Shyamoli Mukherjee[6]

[1]Department of Physics, Catholic University of America, Washington, DC, USA, [2]Heliophysics Science Division, NASA Goddard Space Flight Center, Greenbelt, MD, USA, [3]Finnish Meteorological Institute, Helsinki, Finland, [4]Global Modeling and Assimilation Office, NASA Goddard Space Flight Center, Greenbelt, MD, USA, [5]Goddard Earth Sciences Technology and Research, Universities Space Research Association, Columbia, MD, USA, [6]Indian Institute of Geomagnetism, Navi Mumbai, India

Key Points:
- The horizontal magnetic data recorded at Rome during the August–September 1859 storms is tabulated and converted to nanoteslas
- The reported horizontal deviation of ∼3,000 nT is examined and found to be consistent with an expanded auroral oval
- Maximum changes of around 420 nT min^{-1} are estimated for Rome during the morning of 2 September 1859

Correspondence to:
S. P. Blake,
sean.blake@nasa.gov

Citation:
Blake, S. P., Pulkkinen, A., Schuck, P. W., Nevanlinna, H., Reale, O., Veenadhari, B., et al. (2020). Magnetic Field Measurements from Rome during the August-September 1859 Storms. *Journal of Geophysical Research: Space Physics*, *125*, e2019JA027336. https://doi.org/10.1029/2019JA027336

Received 28 AUG 2019
Accepted 27 MAR 2020
Accepted article online 15 APR 2020

Abstract The geomagnetic storm (or "Carrington event") of 1–2 September 1859 is one of the largest geomagnetic disturbances on record. At the time, it caused widespread disruption to telegraph systems and was accompanied by aurorae seen overhead as far south as ∼29° magnetic latitude. The magnitude of the Carrington event means it remains a popular subject of study in the field of space weather, despite the sparse magnetic measurements available from the time. One set of measurements that is available is from the Rome observatory ("Collegio Romano," magnetic latitude ∼38.6°). Here we transcribe these horizontal magnetic field data and convert them to nanoteslas. We find that the device used at Rome had an operational range of around 305 nT. Despite going off-scale during the storm, the magnetometer at Rome recorded changes of hundreds of nanoteslas per minute and tens of nanoteslas per second in the horizontal magnetic field. Apart from the tabulated data, we also examine the reported off-scale deviation of 3,000 nT at Rome during the storm. While we could not explicitly locate this reported deviation in the tabulated data, we find that this deviation is comparable to magnetic variations seen at auroral latitudes for modern large magnetic storms, indicating that Rome was in the auroral oval during the morning of 2 September 1859. By comparing this large off-scale deviation to modern geomagnetic data, we estimate that Rome may have experienced a maximum change of 420 nT min^{-1}.

1. Introduction

The potential for large geomagnetic storm events to damage ground infrastructure is well known (Oughton et al., 2017). Variations in the Earth's magnetic field induce currents (GICs) which flow through man-made conductors such as railways (Eroshenko et al., 2010), pipelines, and power grids (Pirjola, 2000). In extreme cases, these currents can damage transformers or precipitate a voltage collapse in a network. In recent decades, the Hydro-Québec power systems was disrupted for several hours during the March 1989 storm (Bolduc, 2002). Sweden experienced a transformer failure during the October 2003 storm, leading to a blackout (Pulkkinen et al., 2005). These "high-impact, low-frequency storms," although rare, can be costly. As such, numerous studies have been conducted into quantifying the physical effects of rare but extreme geomagnetic storms. These include magnetohydrodynamic simulations (Ngwira et al., 2013a, 2013b) or statistical estimates from the distribution of historical geomagnetic data (Love et al., 1861; Pulkkinen et al., 2008, 2012) and reconstructions of historical geomagnetic storms (Hayakawa et al., 2020; Love et al., 2019).

The Carrington storm of September 1859 is one of the largest geomagnetic storms on record. This event (which followed the smaller 29 August disturbance) is famous for being preceded by the first visual observation of a solar flare (Carrington, 1859; Cliver & Dietrich, 2013; Hayakawa et al., 2019; Hodgson, 1859; Silverman, 2006; Tsurutani et al., 2003), and its effects were widely publicized in newspapers around the world. These effects included disruption of telegraph systems across Europe and North America (Boteler, 2006a; Muller, 2014), as well as aurora seen as far equatorward as ∼22° in magnetic latitude: the Caribbean Sea, Chile, and southern Japan (Green & Boardsen, 2006; Hayakawa et al., 2016, 2018; Nevanlinna, 2006).

Geomagnetic storms can be characterized by the disturbance storm-time index (Dst), a proxy for the energy in the ring current during a storm (Gonzalez et al., 1994). This value is calculated as an hourly average of four midlatitude magnetic observatories. For the Carrington event, estimates for minimum Dst have ranged from −850 nT to −1,150 nT in the hourly average (Gonzalez et al., 2011; Siscoe et al., 2006) and up to −1,760 nT with spot value (Tsurutani et al., 2003).

The lack of in-scale magnetic measurements for this period has made a definitive Dst calculation impossible, although recent studies have estimated that a Dst closer to around −900 nT is more appropriate for the Carrington event (Cliver & Dietrich, 2013; Gonzalez et al., 2011). This estimate for Dst puts the Carrington event on par with other large historical storms, such as the February 1872 and May 1921 storms (Hayakawa et al., 2018b; Love et al., 2019). For comparison, the March 1989 and October 2003 storms have minimum Dst values of −589 and −383 nT, respectively. Despite the sparsity of magnetic observations, the September 1859 storm event is a valuable example of a geomagnetic superstorm. By studying this period, we can gain new physical insights into superstorm dynamics.

The August and September 1859 storms occurred during a time when geomagnetic observatories were still uncommon across the globe relative to today. Geomagnetic observatories only became widespread after 1834, when Gauss and Weber set up the "Göttingen Magnetic Union," a network of European observatories which measured the intensity of the Earth's magnetic field with individually calibrated instruments (Stern, 2002). Following this, observatories were erected at various sites in the British Empire (Collier, 2014; Goodman, 2018), as well as territories controlled by the Russian Empire (Mandea et al., 2010; Nevanlinna, 2008, 2014; Nevanlinna & Häkkinen, 2010; Tyasto et al., 2009). By 1859, many of these observatories were operating, although most magnetic instruments recording went off-scale during the most disturbed period of the storms. A notable exception of this was the magnetic observatory at Colaba, India (Gawali et al., 2015), which did not go off-scale (Kumar et al., 2015; Tsurutani et al., 2003). In addition, with the exception of observations in Kew and Greenwich, observations at the time were taken manually. This means that data points were often measured at irregular times and contained long gaps between observations.

Between the end of 1859 and 1861, Prof. Elias Loomis of Yale compiled auroral sightings and magnetic measurements during the Carrington event storms from around the world. These eight articles (compiled in Shea & Smart, 2006) were published in the *American Journal of Science* and include magnetic intensity and declination measurements taken in observatories from places as diverse as Toronto, Christiania, Alabama, Brussels, Paris, Greenwich, St. Petersburg, Catherinenburg, Barnaul, Nerchinsk, Melbourne, and Rome. In addition, Loomis's reports documented auroral sightings from other locations, as well as reports of geomagnetically induced currents which disrupted telegraph systems across the Northern Hemisphere.

The contribution to these articles from Rome is a copy of a letter from Angelo Secchi, the director of Italy's first magnetic observatory and noted astronomer. Aside from Secchi's work recording the geomagnetic field at Rome, he is known for being the first to propose star classification based on their spectra (Altamore et al., 2018) and for depicting the Carrington active region (Hayakawa et al., 2019) among other significant contributions to astronomy. This letter, which appears in Loomis (1861), describes aurora seen from Rome as well as disturbances recorded in the magnetic declination and force. In this letter, Secchi writes *"Sept. 2, at 7 A.M., the magnets were very much disturbed … The bifilar indicated a diminution of the horizontal component, amounting to 0.129 or about one-eighth of its mean value"*, where the *bifilar* is a magnetic instrument designed by Gauss used to measure variations in the horizontal magnetic force (see below). The magnitude of the horizontal magnetic field at Rome for 1859 is approximately 22,500 nT according to the gufm1 magnetic field model (Jackson et al., 2018). The reported deviation of 0.129 therefore represents a change of around 3,000 nT. The geomagnetic latitude of Rome in 1859 is 38.6°N according to the gufm1 model. The 3,000 nT deviation is extremely large for so low a geomagnetic latitude, and no similar deviation has been measured at magnetic latitudes below 40°N since the 1980s (Thomson et al., 2011). As such, the data point deserves more detailed investigation.

In addition to the letter which appears in Loomis (1861), two other sources for Rome in 1859 are considered in this paper. These are a French letter which appears in the scientific journal *Comptes Rendus* (Secchi, 1859a) and the annual report for the Collegio Romano Observatory (Secchi, 1859b). The French letter (Secchi, 1859a) appears to be the original copy of the Loomis (1861) letter and contains more descriptive information as well as measurements from the observatory's collection of magnetic instruments. This letter is translated to English and given in Appendix A. Secchi (1859b) contains detailed descriptions of the magnetic instruments used, as well as a more complete data set for the disturbed storm period of 28 August to 3 September 1859. These data, including translated footnotes, are given in Appendix B. Using these sources, we investigate the variations reported in the horizontal magnetic field during the August–September 1859 storms.

Previous studies such as Boteler (2006a) and Cliver and Dietrich (2013) reported on the 3,000 nT deviation at Rome, and by comparing it to other magnetometers recorded around the world during the Carrington event, determined that it was at least partly due to auroral activity. Similarly, Ptitsyna et al. (2012) presents the data from Secchi (1859b) in *divisions*, the native unit used to measure the horizontal force and compares the timing of the variations to magnetic observatories recording in Russia. As far as we are aware, however, the Secchi (1859b) data set has not been converted to modern units (i.e., nT) and been made available to other researchers. In addition, the operational range of the bifilar magnetometer used at the Rome observatory has not been examined in any detail.

In this study, we compile the horizontal magnetic force data taken at the Rome observatory during the August–September 1859 storms. These data are converted to modern units using the description of the magnetometer given in Secchi (1859b), and the limitations of the bifilar magnetometer used at the observatory are analyzed. The reported 3,000 nT deviation on 2 September is given special attention, and this value is put into context with modern magnetic measurements.

2. The Bifilar Variometer at the Rome Observatory

The magnetic observatory at Rome was the first to be established in Italy in 1853 and was directed by Angelo Secchi, the famous Italian astronomer and scientist (Ptitsyna & Altamore, 2012). The observatory was located within the Collegio Romano (41.9°N, 12.48°E). This observatory housed state-of-the-art scientific instruments to measure different aspects of the Earth's magnetic field. These included a declinometer, a horizontal magnetometer for absolute measurements, a balance magnetometer for vertical measurements, and a bifilar or "two-wire" magnetometer for variations in the horizontal magnetic field. In this study, we focus on analyzing the variations in the horizontal magnetic field at the Rome observatory. In terms of space weather studies, these horizontal variations are particularly important drivers of phenomena such as geomagnetically induced currents (Pirjola, 2003). We have transcribed also the measurements for the declinometer and vertical magnetometer as they are recorded in Secchi (1859b), although we do not further analyze these data.

The bifilar or two-wire magnetometer in use in Rome in 1859 was of a model invented by C. F. Gauss in the 1830s. In the following decades, the device soon became popular enough to be used at different magnetic observatories around the world, including Helsinki (Nevanlinna, 1997), Dublin (Lloyd, 1842), and Prague (Valach et al., 2019). Its main components were a magnet suspended from a height by two wires and an eyepiece to view the magnet set on a pillar some meters away. The suspended magnet was allowed to rotate with the varying horizontal geomagnetic field, with the angle at which this magnet stopped rotating determined by the equilibrium of the magnetic force acting on the magnet and the torsion of the wires which suspended it. The eyepiece was used to view a scale reflected off a mirror attached to the suspended magnet. Depending on the angle of the magnet, a different division on the scale would be shown via the eyepiece. From this, the change in intensity of the horizontal magnetic field can be determined as a fraction of the total horizontal magnetic field intensity. A similar magnetometer used in Helsinki from 1844–1910 is shown in Nevanlinna (2006).

Chapter 6 of Secchi (1859b) outlines in more detail the setup and operation of the magnetic instruments that were installed at the Rome observatory. The description given of the two-wire magnetometer closely follows the description given in Lloyd (1842) for a similar instrument in the Magnetical Observatory of Dublin. A modern description of a similar instrument in Helsinki is given in Nevanlinna (1997).

When the bar magnet is oriented perpendicular to the magnetic meridian (by means of adjusting the two-wires that suspend the magnet), it is free to rotate in the horizontal plane with the Earth's magnetic field acting upon it. It will do this until this magnetic force is balanced by the torsion in the two suspending wires. This balance of forces is given by

$$m\,X = \frac{Wa^2}{l}\sin(v) \tag{1}$$

where m is the magnetic moment of the magnet, X is the horizontal component of the Earth's magnetic field, W is the weight of the magnet, a is the separation of the wires, l is their length, and v is the angle of torsion in the wires. From this setup, the absolute intensity of the horizontal magnetic field can be determined provided all of the components are known to a high degree of precision (Lloyd, 1842). In practice, however, the instrument was used to measure variations in the intensity. If we differentiate the left-hand side with respect to the angle v, we get

$$\frac{\Delta(m\,X)}{\Delta v} = \frac{Wa^2}{l}\cos(\mathrm{v}) \tag{2}$$

Dividing by equation (1) gives

$$\frac{\Delta(m\,X)}{(m\,X)} = \Delta v\ \cot(v) \tag{3}$$

The change in the horizontal magnetic field can therefore be expressed in terms of the baseline or total magnetic field and the change in the angle v. This change in angle can be expressed as

$$\Delta v = \Delta\ n\ \alpha \tag{4}$$

where Δn is the number of divisions which pass by the eyepiece, and α is the angle corresponding to each division of the scale. The change in the force acting on the magnet between two times is therefore related to the number of the divisions on the scale by

$$\frac{\Delta F}{F} = K\ \Delta n \tag{5}$$

where $F = mX$ and $K = \alpha\cot(v)$. Finally, as Lloyd (1842) notes, the change in temperature will affect the magnetic moment m. The change in temperature is related to the change in magnetic moment by

$$-\frac{\Delta m}{m} = q\ \Delta t \tag{6}$$

where Δt is the change in temperature, and q is an experimentally determined change in magnetic moment per degree change. Since $F = mX$,

$$\frac{\Delta F}{F} = \frac{\Delta X}{X} + \frac{\Delta m}{m} \tag{7}$$

Substituting equation (6) into equation (7), we arrive at

$$\frac{\Delta X}{X} = K\ \Delta n + q\Delta t \tag{8}$$

This equation allows us to determine the change in horizontal magnetic field from change in divisions and degrees fahrenheit. The temperature correction coefficient q was calculated by Secchi by heating the bifilar magnetometer and measuring the corresponding change in divisions Δn over 2 days. From his calculations, Secchi estimated that $q \approx -0.836$ divisions per degree change in Fahrenheit.

3. Solar Quiet Measurements for June 1859

The solar quiet variation in the Earth's magnetic field can be seen at all latitudes when there is no space weather related geomagnetic activity. This diurnal variation in the Earth's magnetic field is primarily caused by thermally excited solar tides in the ionosphere (Yamazaki & Maute, 2017). Although the solar quiet variations will change with time of year and geomagnetic secular variation, two sets of measurements taken at the same location during the same time of year and magnetically quiet conditions will have similar shapes, regardless of the time interval between recordings. This can be used to help identify a time convention used to record historical magnetic data (Boteler, 2006b).

Figure 1 shows a series of magnetic measurements taken at the Rome observatory at different time periods during 1859. The time series are for a declinometer (top), two-wire magnetometer (middle), and vertical magnetometer (bottom). The recorded declinometer and horizontal time series for 27–30 June 1859 are shown enclosed by a blue and a red box, respectively. Both of these time series show a distinctive solar quiet curve, indicating that the time period was magnetically quiet. These time series were digitized and compared

Figure 1. Measurements taken at the Rome Observatory during 1859. The time series are for a declinometer (top), two-wire magnetometer (middle), and vertical magnetometer (bottom). The blue and red boxes enclose the declinometer and horizontal measurements taken for 27–30 June 1859. From Secchi (1859b).

to modern solar quiet magnetic data measured in June 2009 at the L'Aquila INTERMAGNET observatory (AQU: 42.38°N, 13.32°E, ≈88 km from Rome).

There are a number of considerations to take into account when comparing modern 1-min digital time series data with historical analog recordings such as shown in Figure 1. Vector geomagnetic field measurements from modern INTERMAGNET observatories are measured digitally and have standards for resolution (0.1 nT), dynamic range (6,000 nT at mid-latitude), sampling rate (1 Hz), time-keeping accuracy, thermal stability (0.25 nT/°C) and maximum data drift (5 nT/year) (standards can be found at www.intermagnet.org). In contrast, magnetometers from 1859 often had only a limited dynamic range (as will be shown for the Rome bifilar in the next section), and/or required the observer to manually take measurements, which often led to large gaps between measurements. For disturbed time periods, Viljanen et al. (2014) found that hourly spot measurements (typical of historical magnetic observatories) could significantly underestimate changes in the magnetic field when compared to 1-min data. For this section, we are concerned with the low-amplitude variations of the solar quiet curve.

The bifilar horizontal magnetic field data were converted to nanoteslas using the method described in the previous section. Secchi (1859b) notes that before these measurements were taken, the torsion angle of the two-wire magnetometer was set at 1.75 arc-min and ν was initially set at 75°21′. With an estimated horizontal force of $H = 22{,}500$ nT, and excluding temperature variations, equation (8) becomes

$$\Delta H(\mathrm{nT}) = \Delta n \times 22,500 \times 0.0001331 \tag{9}$$

for June 1859. This means that a change of a single division viewed through the eyepiece should therefore correspond to a change of ≈3 nT in the horizontal magnetic field. The converted horizontal time series are shown in red in the top panel of Figure 1. The declination time series was simply normalized. This is shown in blue in the second panel of Figure 1.

June 2009 was a geomagnetically quiet period, with a number of consecutive 4-day periods with minimum Dst > -5 nT. For each of these 4-day periods, the L'Aquila magnetic data (horizontal and normalized declination) were overlaid and time-shifted between −120 and +120 min. Correlation coefficients were then calculated. As the 1859 data were spot recordings taken at irregular time intervals (ranging from 76 s to several hours between measurements), the 1-min L'Aquila data were downsampled to the Rome 1859 recorded times.

Figure 2 shows the digitized 1859 data with L'Aquila data measured from 6–9 June 2009. From the top plot, the converted measurements taken in June 1859 compare well to the solar quiet variations measured in L'Aquila, both in shape and approximate amplitude. While the amplitudes of the two time series are similar, the amplitude of the B_Y solar quiet variation has been shown to be dependent on solar activity number (Takeda, 2013), and we note here that June 1859 and June 2009 had significantly different monthly mean sunspot numbers, situated almost in the solar maximum and minimum, respectively (≈165 and 6, respectively, http://www.sidc.be/silso).

The horizontal magnetic field and declination time series from 1859 are highly correlated with the modern time series. Peak correlation occurs when time shifts of +16 and +18 min are applied to the modern horizontal and declination time series, respectively. Peak correlation time shifts ranged from −32 to +30 min when the other quiet periods from June 2009 were used as a comparison.

The modern L'Aquila data were measured in UT. While it is not explicitly outlined in Secchi (1859b) which time convention was used for the measurements at Rome in 1859 (i.e., local civil time, Greenwich time, or Göttingen time), the most obvious assumption would be that the data were recorded in local civil time. This is supported by the language used by Secchi in both the margins of Figure 1 and Secchi (1859b). The terms *midday* and *midnight* are used, as well as *6a.* and *6p.* for a.m. and p.m. These indicate that Secchi was making his observations in local civil time (Boteler, 2006b).

Observations made in local civil time at Rome should best correlate with modern data recorded in UT when a time shift of $\Delta\tau = +50$ min is applied to the modern data (as noon in Rome is ≈50 min before noon in Greenwich). While this appears not to be the case for the comparisons we made, we note the broad peaks in the correlation plots and the uncertainty which arises when comparing modern digital data to digitized hand-drawn data (as in Figure 1). Coupled with the terms used in Secchi (1859b) and the lack of an explicit

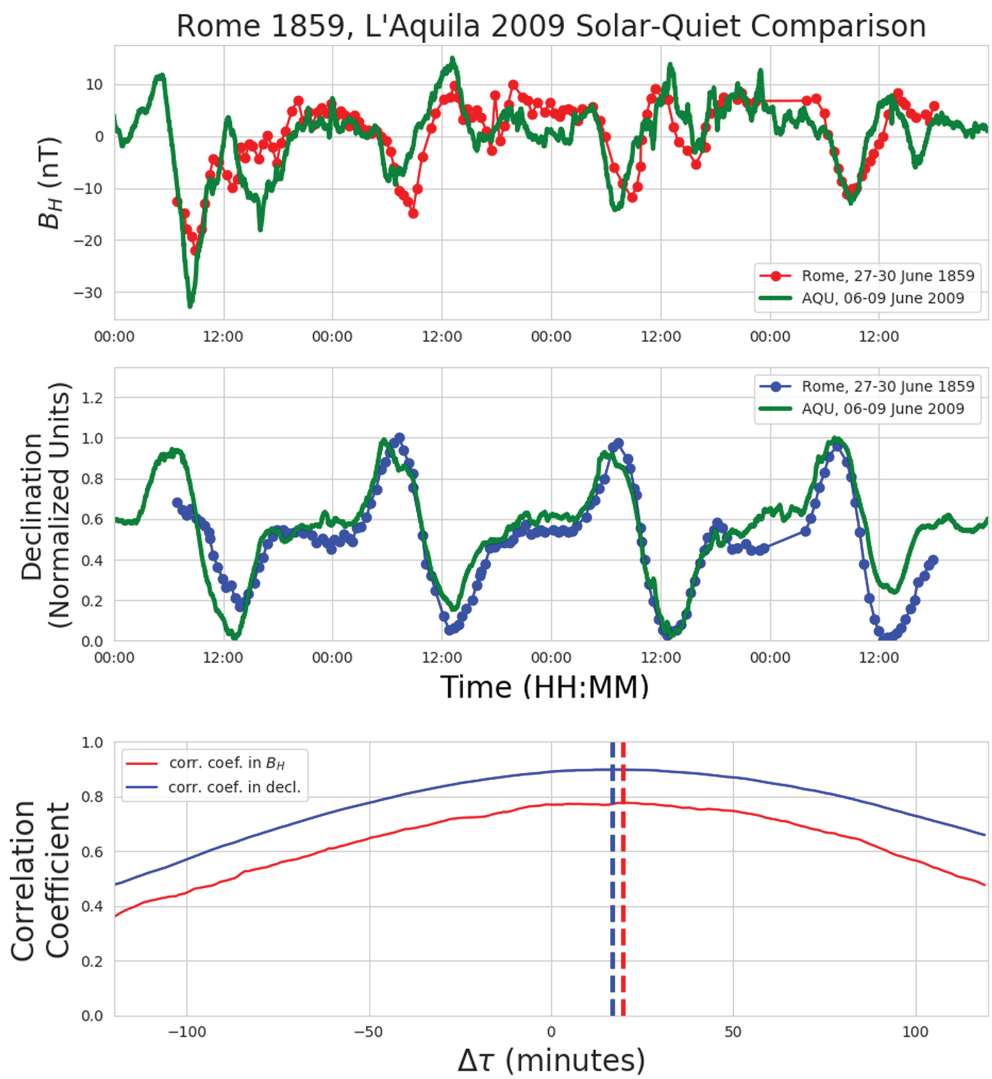

Figure 2. Magnetic data for two solar quiet periods: 27–30 June 1859 at Rome, and 6–9 June 2009 at L'Aquila. (top) Horizontal magnetic field. (middle) Normalized declination. (bottom) Correlation coefficient as the L'Aquila data is shifted by $\Delta\tau$ min. The red and blue lines correspond to horizontal and declination, respectively. Vertical dashed lines correspond to maximum correlation.

declaration of time convention, we find that the local civil time recording is most likely to have been used in the Collegio Romano in 1859.

4. Measurements During 29 August to 3 September

Tabulated data for the 29 August to 3 September period in Secchi (1859b) are given in Appendix B. These data list times of observations, measurements from the declinometer, bifilar, and vertical magnetometers (each given in divisions), as well as infrequent thermometer readings. In addition, footnotes appear beside times of interest. These are where Secchi records unusual activity with the instruments ("The run of the declinometer is frightening") or some meteorological observations ("Broken cirrostratus cloud bands from N to S"). Some of the fields in the table lack measurements and instead have abbreviated terms. These terms and our interpretation of them, as well as the footnotes recorded by Secchi are also given in Appendix B.

These data were converted to nanoteslas using equation (8). It is recorded by Secchi (1859b) that the torsion of the wires of the bifilar magnetometer was adjusted on 19 July 1859 as he deemed the instrument too unstable. The angle ν was changed to be 77°15′. This gives

$$\alpha\ \cot(\nu) = K = 0.00011519 \tag{10}$$

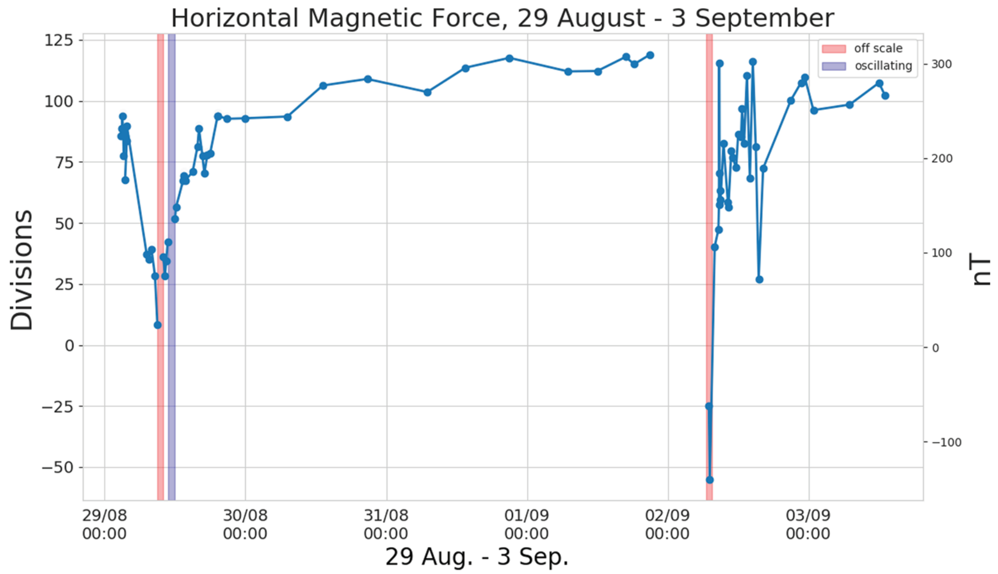

Figure 3. Tabulated data for 29 August to 3 September. Left axis denotes the divisions recorded by Secchi. Right axis is for nanotesla values calculated with equation (11). Areas shaded red are off-scale, and areas shaded blue were oscillating too quickly to measure, as recorded by Secchi (1859b).

For the August–September 1859 storms, the final equation for the change in the horizontal magnetic force is therefore related to divisions in the scale and temperature by

$$\Delta H(\mathrm{nT}) = (\Delta n \times 2.59) + (-2.17 \times \Delta t) \tag{11}$$

For all of the measurements listed in chapter 9 of Secchi (1859b), the maximum value recorded by the magnetometer was 127.7 divisions. The minimum recorded value before the instrument was deemed to be off-scale was 10 divisions. This gives an operational range of at least 117.7 divisions, or approximately 305 nT using equation (11). From Loomis (1861), we are also told "The instruments for measuring the horizontal and vertical force both passed beyond the range of their scales, showing that the variation of the horizontal force must have been at least 0.0135." A decrease of the average horizontal magnetic force by 0.0135 is ≈304 nT or 117.4 divisions. This further indicates that the operational range of the magnetometer was ≈305 nT.

Figure 3 shows the recorded divisions, as well as the time series in nanotesla converted using equation (11) from 29 August to 3 September 1859. The Δt term was calculated as the difference from a mean temperature of 77.6 °F. The times mentioned below are as given in Secchi (1859b), unless otherwise endorsed.

4.1. 29 August to 1 September

Whereas most of the measurements taken for storms in chapter 9 of Secchi (1859b) begin at approximately 07:00, the magnetic recordings for 29 August 1859 begin at 02:45. They were taken by an assistant of Secchi's after he noticed an auroral display to the north of Rome (see Appendix B). The magnetic instruments were already oscillating strongly when measurements were taken. The horizontal force decreased to a minimum of 10 divisions of the scale at 09:00, and at 09:40 it was off-scale for 20 minutes. As noted above, this is a deviation from the average of at least 305 nT. At 11:30, the bifilar oscillated too much for an accurate reading, with the footnote stating that it varied by 10–12 divisions (≈30 nT) in a few seconds. The horizontal magnetic field gradually recovered over the course of the rest of the day, and Secchi states that for the next two days (30 August and 1 September) "This and the following day are calmer, but not entirely." For these two days, seven measurements are recorded, and they range from 94–118.2 divisions (a change of 62 nT). These are the only measurements on record for those days, despite the vertical magnetometer being off-scale for one measurement on 1 September. Unfortunately, unlike at the Kew observatory, there is no measurement of the magnetic crotchet caused by the white-light flare at 11:18 GMT (Carrington, 1859; Hodgson, 1859; Stewart, 1861), as the measurements taken at that time were too infrequent.

4.2. 2 September

The recordings of 2 September begin at 07:00 with negative bifilar measurements. These negative values are unique in Secchi (1859b), and we are told "The bifilar sits at −55 of temporary scale, which is −16 compared to the usual beyond zero." This indicates that the disturbance was beyond the normal scale of the bifilar magnetometer and that Secchi employed a temporary scale to capture the variations. At 08:00, the values return to positive, peaking at 08:46 with 115 divisions. At this time, Secchi notes "Values are now at 115 in the added scale, that is −45 beyond the zero. Since the usual mean is 100, the oscillation has been of 145 marks below the mean, when falling, and about 17 when raising." It is unclear if this note means that the temporary scale was employed until 08:46. A note for 21:00 says that between 08:30 and 21:00, the bifilar changed from 30–115 divisions. The minimum and maximum recorded values for the day in the data tables (excluding the negative values) are 27 (at 15:30) and 115 (at 08:46), respectively. This would indicate that the value of 115 divisions at 08:46 was in the regular scale.

Unfortunately, no further mention of the temporary scale is in the notes accompanying the data table, and we have been unable to determine exactly how the negative values relate to the horizontal magnetic force from Secchi (1859b) alone. For the vertical measurements, it is recorded at 10:30 on 29 August "The vert. is placed back within the scale with a piece of iron: this will still allow to evaluate excursions." No such interference with the two-wire magnetometer is recorded. As mentioned above, Secchi (1859a) states that the horizontal force decreased by ≈0.129 times the average horizontal magnetic field (or 3,000 nT) at approximately the time the temporary scale was reportedly used. No mention of this deviation of 0.129 is mentioned directly in Secchi (1859b). This large deviation is discussed more in detail in the next section.

After 08:46, all of the recorded values for the bifilar magnetometer appear to be in the normal operating range, although they oscillate considerably. Some readings are given as a range, indicating that the horizontal magnetic field was varying quite quickly. This can be seen at 08:50, with the bifilar measurement recorded as 50–90 divisions (103.6 nT). It is unclear how long it took for the magnetometer to vary by this much, possibly over a few seconds. Assuming the 115 divisions measured at 08:46 are in scale, the magnetometer varied by at least 136 divisions (352 nT) over a period of 6 min (08:44–08:50). The magnetometer remained disturbed for the majority of the rest of the day, although there is no indication that it went off scale again.

5. The 3,000 nT Off-Scale Measurement

The variation of 3,000 nT that is recorded in Secchi (1859a) and Loomis (1861) corresponds to a change of ∼1,150 divisions. This is equivalent to a change in the angle of the magnet by ∼33°. It is unclear how this was estimated. Perhaps this change was measured by eye, as the change in the angle would have been clearly visible. This change reportedly happened between 07:00 and 07:30 in Rome, but as measurements only began at 07:00, we do not have any indication as to exactly when the disturbance started. We can, however, compare the Rome data to stations that were continuously recording. Two such stations are Colaba, India (18.9°N, 72.8°E) and Kew, England (51.5°N, 0.2°W). These data, along with the time series for Rome are shown in Figure 4.

The Kew magnetogram trace and Colaba data for this figure are given in Greenwich mean time (GMT). For this figure, the Rome data were assumed to be recorded in local civil Rome time, and a time shift of −50 min was applied to the time series. The Kew magnetogram trace (top panel in Figure 4) has not been converted to nT, and is given only to illustrate the timing of the storm. The storm commencement occurs at approximately 04:40 on the morning of 2 September in Kew. From 05:00 the Kew magnetogram goes off-scale, only coming back into scale at 07:45. Following this, the magnetogram remains disturbed for several hours.

In Colaba, the magnetic field decreases by ≈1,755 nT from 05:00 to 06:30. It quickly recovers ≈1,300 nT until 07:00, after which the time series remains disturbed for several hours, though it varies only in the range of a few hundred nanoteslas. This negative excursion and quick recovery has been variously attributed to magnetospheric, ionospheric, or a combination of both magnetospheric and ionospheric causes (Cliver & Dietrich, 2013, and references therein). The reported 3,000 nT deviation at Rome (shaded blue region) can be seen to occur during the time period where the Kew magnetogram was off-scale, and as the Colaba data were rapidly decreasing in amplitude. As the first measurement in Rome was at 06:10 GMT (07:00 local Rome time), the recorded 3,000 nT deviation may not have been the worst disturbance seen that morning.

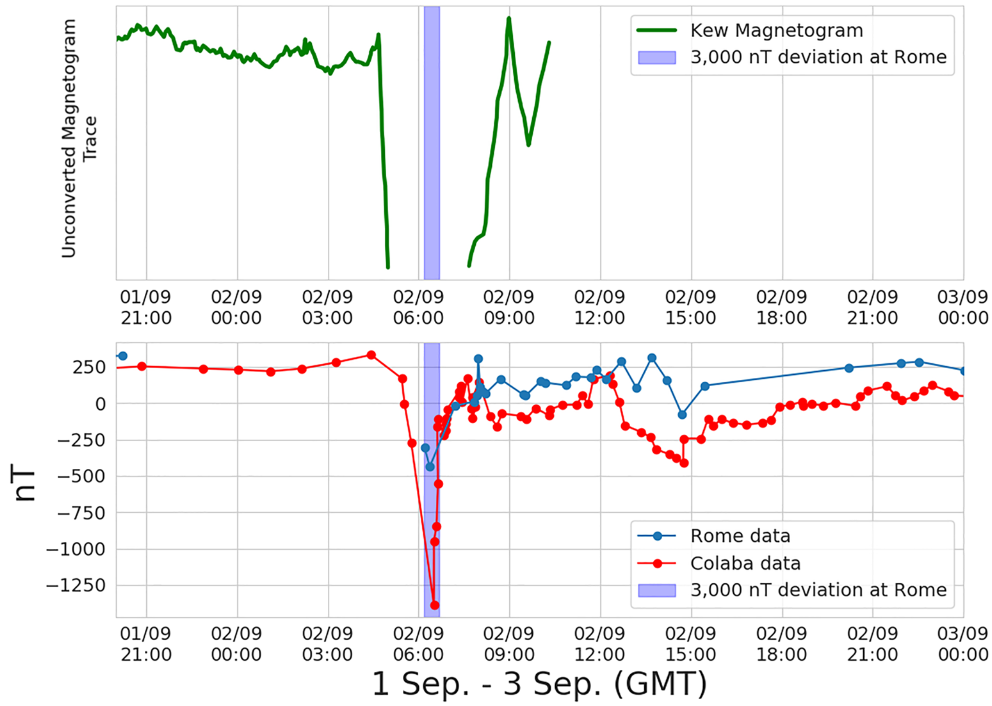

Figure 4. Comparison of the horizontal magnetic field at Kew (top) and Rome and Colaba (bottom) for 1–3 September 1859. The magnetogram trace from Kew has not been converted to nanoteslas for this plot. A time shift of −50 min was applied to the Rome data. The reported 3,000 nT deviation reported in Secchi (1859a) (shaded blue column) occurs when the Kew magnetogram was off-scale and as the Colaba data was sharply decreasing.

As mentioned in section 3, there remains uncertainty regarding the correct time convention used in Rome. In any case, whether the Rome data were measured in local Rome time, Greenwich time or Göttingen time, the recorded 3,000 nT deviation at Rome appears to have coincided broadly with the largest disturbances in both England and India.

5.1. Comparison With Modern Geomagnetic Storms

Next, we contextualize the reported variation of 3,000 nT with modern observational data. The 10 largest storms from 1989 onward ranked by negative Dst were examined. These storm periods are given in Table 1. Data for the March 1989 storm were downloaded from SuperMAG, and from INTERMAGNET for each of the other periods. For each of the listed storm periods, a magnetic latitude and maximum ΔB_H deviation

Table 1
The 10 Modern Geomagnetic Storm Events Used to Compare to the 3,000 nT Deviation in Rome

Date range	Min. Dst (nT)
13–14 Mar 1989	−589
19–21 Nov. 2003	−422
30–31 Mar 2001	−387
29–31 Oct 2003	−383
7–9 Nov 2004	−374
8–10 Nov 1991	−354
15–17 Jul 2000	−301
24–26 Mar 1991	−298
5–7 Nov 2001	−292
9–11 May 1992	−288

Note. They were chosen by minimum Dst values.

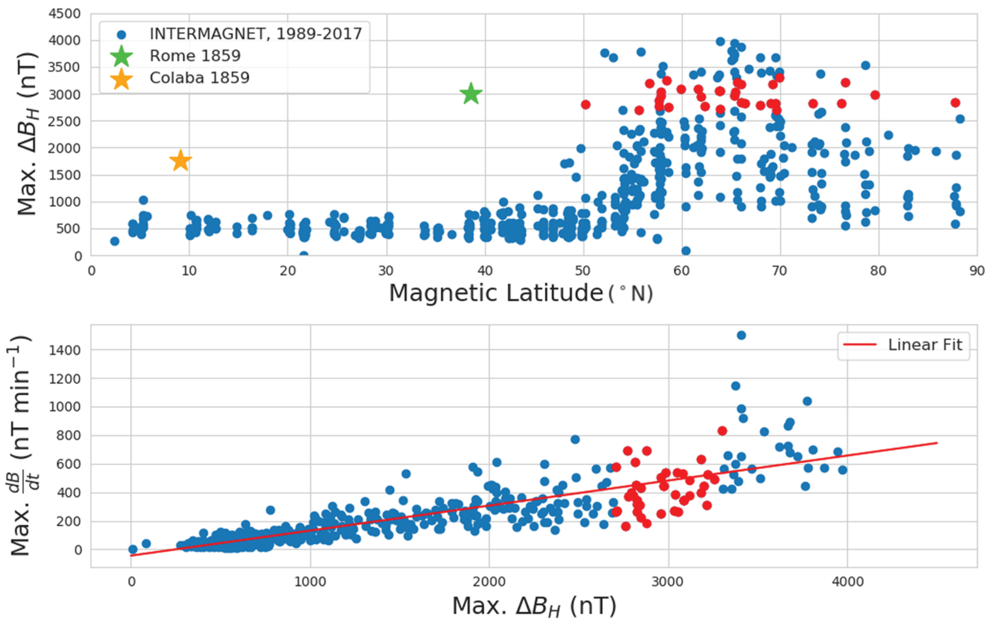

Figure 5. (top) Maximum ΔB_H versus magnetic latitude for the 10 largest geomagnetic storms since 1989. The maximum Rome and Colaba ΔB_H for 1859 are shown as green and orange stars, respectively. (bottom) Maximum $\mathrm{d}B/\mathrm{d}t_{\mathrm{min}}$ versus ΔB_H for the 10 largest geomagnetic storms since 1989. A ΔB_H value of 3,000 nT corresponds to a maximum $\mathrm{d}B/\mathrm{d}t$ of 477 nT min^{-1}. In both plots, the red dots indicate the stations with ΔB_H between 2,700 and 3,300 nT.

were extracted for each site in the northern magnetic hemisphere. These are shown in the top panel in Figure 5. The increase in ΔB_H with magnetic latitude is clearly seen, with the slope increasing rapidly at around 53° magnetic North. The larger ΔB_H values at high latitudes are associated with the auroral current activity during geomagnetic storms (Ngwira et al., 2013c; Pulkkinen et al., 2012). The southward expansion of the auroral currents during geomagnetic storms are a well-known phenomenon (Woodroffe et al., 2016). Although there is uncertainty regarding the exact physical mechanisms which govern the expansion of the auroral current system equatorward, the expansion has been attributed to the saturation of the cross-polar cap potential during geoeffective solar wind drivers (Russel et al., 2001).

As can be seen in Figure 5, there are no sites at Rome's magnetic latitude in 1859 (≈38.6°) with comparable ΔB_H for the 10 recent storms. Only beyond 52°N do sites have ΔB_H larger than 3,000 nT. During the September 1859 storm, the visible aurora was seen overhead as far south as ∼31° invariant latitude, or ∼29° magnetic latitude (Hayakawa et al., 2019). Secchi (1859b) does not explicitly mention nighttime aurroal sightings in Rome for 2 September, although it is mentioned in Secchi (1859a) that "The clouds observed in the heavens had the exact appearance of those of the aurora borealis when it occurs by day, and such as were noticed at Rome Aug. 29th." This may be a description of a daytime auroral sighting. The lack of European auroral sightings during 2 September can be attributed to the large parts of the storm occurring during local daytime hours (Hayakawa et al., 2019). Expansion of the auroral current system to cover at least 38.6° magnetic north could explain the large horizontal magnetic deviation reported by Secchi and the low-latitude auroral sightings elsewhere.

Given the nature of the recordings at Rome, the maximum rate of change of the magnetic field per minute ($\mathrm{d}B/\mathrm{d}t$) is unavailable for the time period before 08:00. The horizontal component of the magnetic field is closely related to the maximum rate of change in the magnetic field (Tóth et al., 2014). For the modern storms listed above, this relationship can be characterized by plotting maximum $\mathrm{d}B/\mathrm{d}t$ against maximum ΔB_H for each of the sites. This is shown in the bottom panel of Figure 5. A line of slope 0.174 best fits the data. Assuming a similar relation exists between $\mathrm{d}B/\mathrm{d}t$ and ΔB_H at Rome in 1859, a maximum $\mathrm{d}B/\mathrm{d}t$ of 477 nT min^{-1} can be expected for a horizontal variation of 3,000 nT.

The sites which had a maximum ΔB_H between 2,700 and 3,300 nT were then analyzed further. For each of these sites, the cumulative frequency distributions of $\mathrm{d}B/\mathrm{d}t$ were calculated. These are shown as red curves

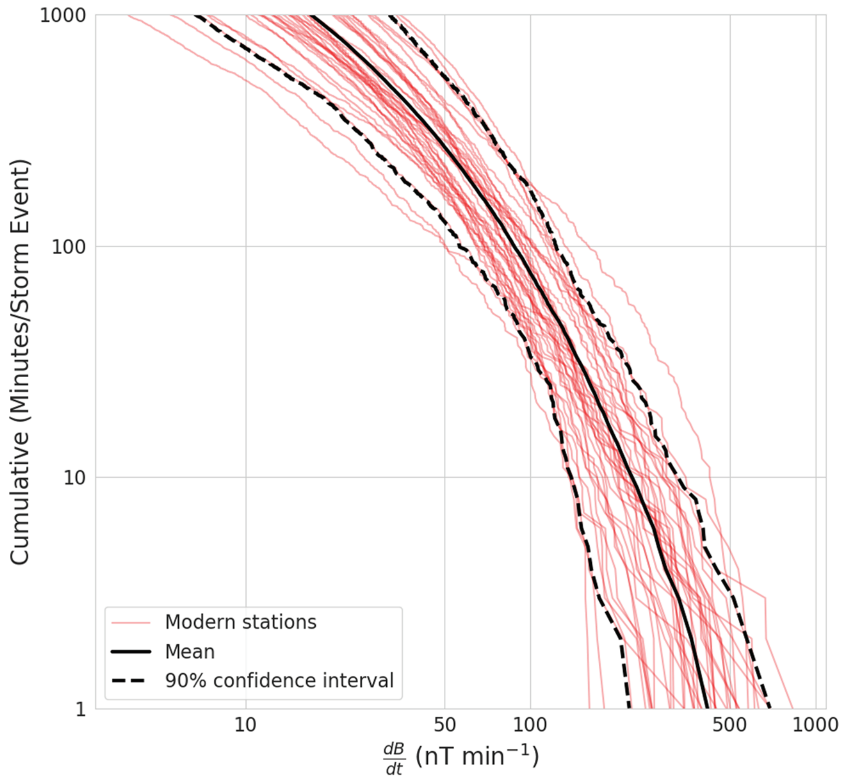

Figure 6. Cumulative distribution of dB/dt for the subselection of modern measurements (red dots in Figure 5). Bold black line is the average of these distributions, and dashed lines are for the 90% confidence interval.

in Figure 6. These curves show the occurrence of dB/dt magnitudes per storm event. From these, the average (solid black line) and 90% confidence intervals (dashed black line) were calculated for every minute, giving an estimate for the cumulative frequency distribution of dB/dt for an observatory which measures a maximum ΔB_H between 2,700 and 3,000 nT. From this fit, such an observatory would expect to see a peak dB/dt of 420 nT min^{-1}, with a 90% confidence interval between 232 and 678 nT min^{-1}. The same observatory is expected to see 10 (not necessarily contiguous) minutes with at least 231 nT min^{-1} (90% confidence interval between 139 and 325 nT min^{-1}). These values are given in Table 2.

6. Conclusion

In this paper, we present the horizontal magnetic field data as recorded by Angelo Secchi in Rome during the August–September 1859 geomagnetic storms. These data, which were recorded using a Gauss bifilar magnetometer, were converted to modern units using the specifications outlined by Secchi (1859b). We determined that the magnetometer could measure variations of ≈305 nT before going off-scale. For both the 29 August and 2 September 1859 storms, the device did go off-scale.

Table 2
Values for the Calculated Cumulative Distributions of dB/dt as given in Figure 6

Minutes		dB/dt (nT min^{-1})	
1,000	7	**17**	32
100	58	**89**	121
10	139	**231**	325
1	232	**420**	678

Note. The bold values are average values. These are flanked by the lower and upper 90% confidence interval values.

Despite this, Secchi recorded very intense changes in the horizontal magnetic field of hundreds of nanoteslas in minutes, and tens of nanoteslas change in seconds. These changes, while large, are not extraordinarily so. Unfortunately, measurements do not exist for the early hours of 2 September, so it is unclear if the measurements that were taken were of the largest variations at Rome that morning. Those measurements which were taken at this time (after 07:00 Rome time) were off-scale. A temporary scale was used for these off-scale measurements, but it is unclear to us how exactly these values should be interpreted.

For the same time period, Secchi (1859a) recorded that an off-scale deviation of ≈3,000 nT ocurred between 07:00 and 07:30 local-time on 2 September 1859, although their original data are not recorded in the tabulated series. By comparing this to other horizontal magnetic field recordings at the time, we have shown that the maximum recorded deviation of 3,000 nT occurs at approximately the most disturbed period of the 2 September storm registered also in both Kew and Colaba.

The reported 3,000 nT deviation at the geomagnetic latitude of Rome in 1859 is unparalleled in modern times, with such a large change in horizontal field strength typically only appearing at higher magnetic latitudes. Expansion of the auroral oval overhead to Rome could account for this large magnetic deviation, as well as the rapid changes in intensity measured there. It is known that the auroral current system expands equatorward during large geomagnetic events, and the Carrington event had particularly low-latitude overhead and visible aurorae.

By analyzing the magnetic time series of modern observatories, a 3,000 nT deviation in the horizontal magnetic field during a geomagnetic storm is expected to have a maximum dB/dt of 420 nT min^{-1}. This large value could have implications for ground infrastructure at low magnetic latitudes (i.e., <50°N). Modern cities with similar magnetic latitudes to Rome in 1859 are Orlando (38.1°), Los Angeles (40.1°), Madrid (41.7°), and indeed modern-day Rome (41.9°).

There are still a number of uncertainties regarding the measurements made at Rome in 1859. From the language in Secchi (1859b), it is likely that the measurements were made using local civil time; however, this is not explicitly expressed. Our comparison of June 1859 and June 2009 solar quiet data shows that there is a high degree of correlation when a time shift of between −432 and +32 min are applied to modern data (while we need to note the significant difference of their background solar activity). Second, as measurements only began in Rome several hours after the sudden commencement was registered in Kew, we do not know the full extent of the horizontal deviation in Rome. Finally, we do not know how the use of the temporary scale relates to the regular bifilar scale. By further examining the Rome data in conjuction with measurements at other European sites, it may be possible to resolve some of these issues in the future.

Appendix A: Letter From Fr. Secchi as Appeared in *Comptes Rendus*

On the magnetic disturbances observed in Rome, 2 September 1859.

The 2 September was a remarkable day, given the large electrical disturbance that manifested itself in the telegraph wires. Professor Pietro Monte had already made the magnetic disturbance observed at Livourne known; I believe that a few details of the observations made while at Collegio Romano will not be without any interest, as there were some particularities that were noted and that seem to have eluded other observers.

The disturbance had already started to show on 1 September. That day, the vertical magnetometer was out-of-scale at 4:00 p.m., indicating a diminution of vertical force. At 7:00 a.m. the following day, 2 September, the bars were found extremely agitated; their oscillations were of 10 and 30 scale divisions. At 7.10 a.m. the westerly extreme position of the declinometer was 3°50′ beyond the normal position. From this moment, the bar returned rapidly toward the east exceeding the average position of 1°23′, where it stopped at 7.30 a.m., having moved through 4°13′ in less than a half hour. This disturbance is astonishing, as the largest recording beforehand was between 45 or 50 min. The bifilar went off-scale; but with the help of an auxiliary scale we found 55 divisions; which is to say that it had deviated at least $2°\frac{1}{2}$, and given that soon after it went up to 115 divisions, the whole vibration reduced into the components of its force amounted to a diminution on the horizontal component of 0.129 or almost $\frac{1}{8}$.

At 8:00 a.m., the declinometer was reading 181 divisions, which is to say 60 divisions to the east of the average position; the bifilar was still under the average position, which is 110 divisions and reading 40 divisions. At this instance, the state of the sky was observed, and it was noted that toward the north, the entire horizon was blocked by a thick fog from which numerous cirri (cirrus clouds) emerged and headed in a northeasterly direction, going beyond the zenith. This state lasted until 9:00 a.m. These clouds were shredded along the edges and varied. The northerly wind (wind coming from the north) was weak.

From 8.30 a.m. to 8.46 a.m., the declinometer was observed oscillating between 138 and 153 divisions, and 127 and 170 divisions, while the bifilar oscillated between 44 and 70 divisions. At 8.46 a.m. the declinometer read 170 divisions, and the bifilar jumped from 30 to 115 divisions. The vertical magnetometer, which remained off-scale, returned to scale for a moment and jumped toward the other side. These sudden movements indicated a considerable increase in force.

After several rather large oscillations, the instruments started to calm a little.

At 9.30 a.m., the position of the declinometer was 116.5, the bifilar 82.0, the vertical 22.0 div.

At 10.20 a.m., the position of the declinometer was 117.4, the bifilar 56.0, the vertical 12.0 div.

The declinometer was around its normal position, but the others indicated a notable and intense variation of inclination. At 3:00 p.m. in the evening, the disturbances increased.

Time	Declinometer div.	Two-wire div.	Vertical div.
14 hr 30 min	94	126	18 to 27
15 hr 00 min	106	72 to 81	30
15 hr 30 min	111	0.0	35
16 hr 15 min	115	72	off scale
Midnight	116.2	99.1	43.5

At 9:00 p.m. in the evening all calmed down, and at midnight all the instruments were almost back in a normal state.

The effect produced by this disturbance increased the vertical component (of force) notably. It had decreased a lot during the month of August, especially in the first 15 days in which the much heightened temperature here had an average maximum of 35.08 °C. The vertical position had hardly changed, although the temperature had decreased to and average maximum of 27.35 °C. After the disturbance, the vertical force had increased by 0.0037, but it seems that it will gradually diminish again.

We will finish with some remarks on this interesting magnetic disturbance:

1. The variations among the three instruments were not simultaneous, but the maxima came at different times for each of them. For the declinometer, the deviation toward the west was stronger than the east, and it even resulted in an increase toward the west of 11 min approximately.
2. These large vibrations are contemporary with the currents observed in the telegraph wires
3. The clouds observed in the sky all had the appearance of those of the aurora borealis phenomenon occurring in daylight and was even observed on 29 August in Rome.
4. It is quite remarkable that these large disturbances coincided with the period of maximum sunspots, and more precisely while a large spot was visible on the disk, even without instruments. We are sending you a sketch of this spot which is quite remarkable in appearance of the filaments and currents form which it is formed, which shows a large agitation.
5. The large rise in temperature that we have had this year in the months of July and August are perhaps not so strange with these solar tribulations.

Appendix B: Data Table From Secchi 1859b

Tables B1 through B4 show the tabulated data for 29 August to 3 September as it appears in pages 235–237 of Secchi (1859b). The numbers in the "Note" column refer to the footnotes translatedhere. Table B5 shows the terms in the tables and our interpretations of them.

B.1. 29 August

Disturbance with beautiful boreal aurora in Rome. From the previous day, especially in the bifilar, a small but not exceptional divergence from the normal place of the instruments was noted. The Bifilar and the Vert had grown at 01:30 AM, when Fr. Rosa noticed the phenomenon and saw two vast lights to the right and to

Table B1
Tabulated Data From Secchi (1859b)

Date (mm/dd)	Time (HH:MM:SS)	Declin. (*div*)	Bifilar (*div*)	Vert. (*div*)	Temp. (°F)	Note
08/29	02:45:00	133 ±	86.9	111.3	78.5	
08/29	02:58:00	136	90	114		(1.1)
08/29	03:00:00	131	95	112		
08/29	03:10:00	130	89	102		
08/29	03:15:00	135	79	105		
08/29	03:25:00	119	87	130		(1.2)
08/29	03:25:30	125				
08/29	03:26:00	110				
08/29	03:29:00	112	69	125		(1.3)
08/29	03:46:00	114	85	120		
08/29	03:48:00	116	91	125		
08/29	07:10:00	122.7	39	fuori		
08/29	07:30:00	116	37	id.	78.9	(1.4)
08/29	08:00:00	120.8	41	id.		
08/29	08:35:00	122.2	30	id.		
08/29	09:00:00	116.6	10	id.		
08/29	09:40:00	115.2	fuori	id.		
08/29	10:00:00	109.2	38	id.		
08/29	10:16:00	102.8	30	id.		
08/29	10:30:00	100	36	51.2		(1.5)

Note. The units for the declinometer, bifilar, and vertical magnetometers are given in the recorded divisions.

Table B2
Continuation of Data From Table B1

Date (mm/dd)	Time (HH:MM:SS)	Declin. (*div*)	Bifilar (*div*)	Vert. (*div*)	Temp. (°F)	Note
08/29	10:45:00	106.5	44	37.2		
08/29	11:30:00	106.5	oscill.	oscill		(1.6)
08/29	11:55:00	113.5	id.	id.		
08/29	12:00:00	110.5	53.2	id.		
08/29	12:10:00	111.3	58	22		(1.7)
08/29	13:23:00	111	69	17		
08/29	13:30:00	110	71	16		(1.8)
08/29	13:45:00	111	69	14.5		
08/29	15:00:00	112.8	72.4	11.2		
08/29	15:50:00	119.9	82.7	fuori		(1.9)
08/29	16:05:00	120.3	90	61		
08/29	16:40:00	119.5	78.9	77.8		
08/29	17:00:00	120.2	71.7	87.5		
08/29	17:30:00	119.5	79.2	89		
08/29	18:00:00	119.3	80	92		(1.10)
08/29	19:15:00	119.5	95	115		
08/29	19:20:00	119.5	95.1	57		
08/29	20:50:00	118	93.9	61.2		
08/30	00:00:00	118.3	94	64.3		
08/30	07:10:00	124.2	94.5	64.5	78	(2.1)
08/30	13:10:00	112	107	74.3		
08/30	20:45:00	118.1	109.5	72	77.6	

Note. The units for the declinometer, bifilar, and vertical magnetometers are given in the recorded divisions.

Table B3
Continuation of Data From Table B1

Date (mm/dd)	Time (HH:MM:SS)	Declin. (*div*)	Bifilar (*div*)	Vert. (*div*)	Temp. (°F)	Note
08/31	07:00:00	124.2	103.9	70.3	77.3	
08/31	13:30:00	111.5	114	80.9		
08/31	21:00:00	120	118.2	77.5	77.7	
09/01	07:00:00	123.3	112	76.1	76.9	
09/01	12:00:00	111.6	112.2	89		
09/01	16:50:00	114	118	fuori		(3.1)
09/01	18:15:00	117.8	115	id.		
09/01	21:00:00	119	119	92	77	
09/02	07:00:00	20–30	−25	fuori in basso		(4.1)
09/02	07:10:00	20–0	−55	… ….		(4.2)
09/02	08:00:00	118	40	fuori		
09/02	08:38:00	138–156	40–54	fuori e rimesso		(4.3)
09/02	08:44:00	149–153	44–70	fuori		
09/02	08:46:00	127–170	115	id.		(4.4)
09/02	08:50:00	144–152	50–90	zero		
09/02	08:55:00	126–131	61–65	id.		(4.5)
09/02	09:00:00	131–134	51–67	id.		
09/02	09:30:00	116.5	82	24	76.3	
09/02	10:15:00	115	58	23±		
09/02	10:20:00	117.4	56	15.8		
09/02	10:50:00	121	79	11.8		
09/02	11:00:00	119.2	76.4	14.3		

Note. The units for the declinometer, bifilar, and vertical magnetometers are given in the recorded divisions.

Table B4
Continuation of Data From Table B1

Date (mm/dd)	Time (HH:MM:SS)	Declin. (*div*)	Bifilar (*div*)	Vert. (*div*)	Temp. (°F)	Note
09/02	11:40:00	118.2	72.5	18.9		(4.6)
09/02	12:00:00	112±	86±	21±		(4.7)
09/02	12:30:00	117±	85±	23±		
09/02	12:40:00	114±	96.5	25		(4.8)
09/02	13:00:00	116	82.2	25.5		
09/02	13:30:00	107	110	28.5		
09/02	14:00:00	116.5	68±	43		
09/02	14:30:00	95±	116	118		(4.9)
09/02	15:00:00	106.2	81	30		(4.10)
09/02	15:30:00	105	27	35		
09/02	16:15:00	111.2	72.2	fuori a 0		
09/02	21:00:00	115	100.4	22.9	77	(4.11)
09/02	22:43:00	118	107.4	30.2		
09/02	23:20:00	114.1	109.7	39.4		(4.12)
09/03	00:50:00	116.5	96.1	43.5		
09/03	07:00:00	121.8	98.1	41.3	76.5	
09/03	12:00:00	107.8	107±	47.7		
09/03	13:00:00	106.4	102±	44		

Note. The units for the declinometer, bifilar, and vertical magnetometers are given in the recorded divisions.

Table B5
Terms and Interpretations for Data Table in Secchi (1859b)

Terms	Interpretation
fuori	out of scale
oscill.	oscillating
id.	indeterminate
fuori in basso	below scale
fuori e rimesso	beyond scale and brought back
zero	zero
±	approximate value
blank space	no measurement

the left of the magnetic north, and red sky. He immediately gave me notice and the following observations were taken.

The positions are approximate, because all three instrumensts are in great agitation. The entire northern part of the horizon is luminous. The light is red and extends from the east to the west even beyond the zenith. At about 2:45 a.m., cirrus cloud coverage spreads through the entire sky, dimming the red light. The aurora was seen also from Civita Vecchia from some sailors, appearing as a column of fire, and thought to be a comet.

(1.1) 02:58 Strong oscillations. The vert. is already off-scale and is estimated, because the scale reaches only 100.

(1.2) 03:25 The run of the declinometer is frightening. The bifilar rapidly oscillates by six divisions.

(1.3) 03:29 At 3:40 a.m. beautiful rockets and columns of an intense white light and pale yellow toward the north can be seen even through the clouds.

(1.4) 07:30 The light disappears almost entirely by 4:00 a.m., but the disturbance is still going on. The position of the bifilar is estimated, because it is outside the scale, then it even goes beyond the line. Inclin. 58°53′.

(1.5) 10:30 The vert. is placed back within the scale with a piece of iron: This will still allow to evaluate excursions. Cirrocumulus formations cover the entire sky.

(1.6) 11:30 Oscillations are so strong that it is impossible to predict the part of the scale in which they will occur: Variations of 10 or 12 marks occur in a few seconds.

(1.7) 12:10 While still holding the piece of iron, the measurement is off scale in the opposite direction. Taken the iron out, it stops at 17.

(1.8) 13:30 The inclinometer is at 57°58′.

(1.9) 15:50 Again off scale from the zero side: It is brought back with a small piece of iron placed on the top.

(1.10) 18:00 The piece of iron that sustains it is removed. This is the first large disturbance observed in Rome, comparable to the ones observed in Germany and in the northern countries. This has been accompanied by the most beautiful aurora that has been seen in Rome for many years. The center of the light is not aligned with the astronomical meridian, but is quite toward the NW, just a little to the west of the chruch of S. Ignazio, which is almost parallel to the magnetic meridian. The aurora was brigher to the west compared to the east, especially toward the end, when the light already weakened was completely dimmed by the rising Sun.

B.2. 30 August

(2.1) 07:10 This and the following day are calmer, but not entirely. We provide the main events for the day.

B.3. 1 September

(3.1) 16:50 The vertical is found off scale. It is brought back within the scale and it stops at 92 divisions. This appears as the precursor of the new disturbance that will erupt on the following day.

B.4. 2 September

(4.1) 07:00 Terrifying disturbance. The declinometer osciallates between 20 and 30 (note, not 120 and 130 as usual, but actually 20 and 30!). The average is taken, also further.

(4.2) 07.10 The bifilar sits at -55 of temporary scale, which is −16 compared to the usual beyond zero. The vertical falls even after being placed back. At 8:00 the sky is covered by cirrus clouds in stripes like plumes, there is thick fog on the horizon to the north, lighter fog elsewhere. At 8:30 the declinometer oscillates between 160 and 140 after having made a colossal run from 20 to this point. The bifilar oscillates between 90 and 10. The vertical keeps being off scale. In the preceding days a large reduction in wind speed was observed and the atmosphere being exceedingly calm.

(4.3) 08:38 Stripes are noted in the sky, from the N toward the SW, appearing as semicircular curved broken plumes.

(4.4) 08:46 Values are now at 115 in the added scale, that is −45 beyond the zero. Since the usual mean is 100, the oscillation has been of 145 marks below the mean, when falling, and about 17 when rising.

(4.5) 08:55 Broken cirrostratus cloud bands from N to S.

(4.6) 11:40 Few cirrus clouds.

(4.7) 12:00 Oscillations

(4.8) 12:40 The vertical oscillates with jumps. When the fraction is not placed, it oscillates.

(4.9) 14:30 From 18 to 27.

(4.10) 15:00 Sudden strong southeasterly wind with gusts.

(4.11) 21:00 Clear sky. This disturbance has been extraordinarily large. The declinomenter has run for about 4°. The bifilar for 0.0105 of the mean horizontal force. By looking at the two extremes, from -117 to 45, the range is enormous. Nothing can be said of the vertical, since it went off scale on both sides. First, before 8:30, went off scale beyond 100; then, after 9:00, went off scale below zero. Between these two times, the action changed side, and the declinometer jumped to 170, and the bifilar went from 30 to 115.

(4.12) 23:20 It appears that the disturbance is calming down. Definitely there must have been some aurora even in daylight in some locations, and even here these strange cirrus clouds must have been related (see before).

B.5. 3 September

3 September, slightly disturbed, but not too much.

Acknowledgments
The results presented in this paper rely on data collected at magnetic observatories. We thank the national institutes that support them and INTERMAGNET for promoting high standards of magnetic observatory practice (www.intermagnet.org). Data were also obtained from the SuperMAG database (http://supermag.jhuapl.edu/info/?page=faq). Dst values were obtained from the World Data Center for Geomagnetism, Kyoto (http://wdc.kugi.kyoto-u.ac.jp/). Sunspot number adata were taken from WDC SILSO (www.sidc.be/silso). Kew observatory magnetograms were obtained from the British Geological Survey (https://www.bgs.ac.uk/data/Magnetograms/home.html). The Colaba (Bombay) magnetogram for the 1–2 September 1859 magnetic storm data is the same data set that appears in Tsurutani et al. (2003), Kumar et al. (2015), and Hayakawa et al. (2018). We extend our thanks to Gary Lynam of the Geneva School of Economics and Management for help with the Secchi 1859 letter. We would also like to thank David Boteler for his constructive comments regarding the timing of the horizontal measurements. Thanks also to Pietro Zucca for his help with the Italian translations and John Grunwell for help sourcing the documents. We thank the two reviewers for their helpful comments and criticisms of this paper. This work was supported by the NASA's Living With a Star program (17-LWS17_2-0042), and the Electric Power Research Institute (EPRI SAA5-2017-4-R26568).

References

Altamore, A., Poppi, F., & Bosco, T. (2018). The Vatican Observatory, Castel Gandolfo: 80th anniversary celebration. *Astrophysics and Space Science Proceedings*, *51*, 185–196. https://doi.org/10.1007/978-3-319-67205-2

Bolduc, L. (2002). GIC Observations and studies in the Hydro-Quebec power system. *Journal of Atmospheric and Solar-Terrestrial Physics*, *64*, 1793–1802. https://doi.org/10.1016/S1364-6826(02)00128-1

Boteler, D. H. (2006a). The super storms of August/September 1859 and their effects on the telegraph system. *Advances in Space Research*, *38*, 159–172. https://doi.org/10.1016/j.asr.2006.01.013

Boteler, D. H. (2006b). Comment on time conventions in the recordings of 1859. *Advances in Space Research*, *38*, 301–303. https://doi.org/10.1016/j.asr.2006.07.006

Carrington, R. (1859). Singular appearance in the Sun. *Monthly Notices of the Royal Astronomical Society*, *20*, 13–15.

Cliver, E. W., & Dietrich, W. F. (2013). The 1859 space weather event revisited: Limits of extreme activity. *Journal of Space Weather and Space Climate*, *3*, A31. https://doi.org/10.1051/swsc/2013053

Collier, P. (2014). *Edward Sabine and the 'Magnetic Crusade', History of cartography lecture notes in geoinformation and cartography*. Berlin: Springer. https://doi.org/10.1007/978-3-642-33317-019

Eroshenko, E., Belov, A., Boteler, D., Gaidash, S., Lobkov, S., Pirjola, R., & Trichtchenko, L. (2010). Effects of strong geomagnetic storms on northern railways in Russia. *Advances in Space Research*, *46*, 1102–1110. https://doi.org/10.1016/j.asr.2010.05.017

Gawali, P. B., Doiphode, M. G., & Nimje, R. N. (2015). Colaba-Alibag magnetic observatory and Nanabhoy Moos: The influence of one over the other. *History of Geo- and Space Sciences*, *6*, 107–131. https://doi.org/10.5194/hgss-6-107-2015

Gonzalez, W. D., Echer, E., Tsurutani, B. T., Clua de Gonzalez, A. L., & Dal Lago, A. (2011). Interplanetary origin of intense, superintense and extreme geomagnetic storms. *Space Science Reviews*, *158*, 69–89. https://doi.org/10.1007/s11214-010-9715-2

Gonzalez, W. D., Joselyn, J. A., Kamide, Y., Kroehl, H. W., Rostoker, G., Tsurutani, B. T., & Vasyliunas, V. M. (1994). What is a geomagnetic storm? *Journal of Geophysical Research*, *99*, 5771–5792. https://doi.org/10.1029/93JA02867

Goodman, M. (2018). From 'magnetic fever' to 'magnetical insanity': Historical geographies of British terrestrial magnetic research (PhD thesis), University of Glasgow. https://theses.gla.ac.uk/30829/

Green, J. L., & Boardsen, S. (2006). Duration and extent of the great auroral storm of 1859. *Advances in Space Research*, *38*, 130–135. https://doi.org/10.1016/j.asr.2005.08.054

Hayakawa, H., Ebihara, Y., Hand, D. P., Hayakawa, S., Kumar, S., Mukherjee, S., & Veenadhari, B. (2018). Low-latitude aurorae during the extreme space weather events in 1859. *The Astrophysical Journal*, *869*, 57. https://doi.org/10.3847/1538-4357/aae47c

Hayakawa, H., Ebihara, Y., Willis, D. M., et al. (2018b). The great space weather event during 1872 February recorded in East Asia. *The Astrophysical Journal*, *862*, 15. https://doi.org/10.3847/1538-4357/aaca40

Hayakawa, H., Ebihara, Y., Willis, D. M., Toriumi, S., Iju, T., Hattori, K., et al. (2019). Temporal and spatial evolutions of a large sunspot group and great auroral storms around the Carrington event in 1859. *Space Weather*, *17*, 1553–1569. https://doi.org/10.1029/2019SW002269

Hayakawa, H., Iwahashi, K., Tamazawa, H., Isobe, H., Kataoka, R., Ebihara, Y., et al. (2016). East Asian observations of low-latitude aurora during the Carrington magnetic storm. *Publications of the Astronomical Society of Japan*, *68*, 99. https://doi.org/10.1093/pasj/psw097

Hayakawa, H., Ribeiro, P., Vaquero, J. M., Gallego, M. C., Knipp, D. J., Mekhaldi, F., et al. (2020). The extreme space weather event in 1903 October/November: An outburst from the quiet Sun. *The Astrophyisical Journal Letters*. https://doi.org/10.3847/2041-8213/ab6a18

Hodgson, R. (1859). On a curious appearance seen in the Sun. *Monthly Notices of the Royal Astronomical Society*, *20*(1), 15–16. https://doi.org/10.1093/mnras/20.1.15a

Jackson, A., Jonkers, A. R. T., & Walker, M. R. (2018). Four centuries of geomagnetic secular variation from historical records. *Philosophical Transactions of the Royal Society A*, *358*, 957–990. https://doi.org/10.1098/rsta.2000.0569

Kumar, S., Veenadhari, B., Tulasi Ram, S., Selvakumaran, R., Mukherjee, S., Singh, R., & Kadam, B. D. (2015). Estimation of interplanetary electric field conditions for historical geomagnetic storms. *Journal of Geophysical Research: Space Physics*, *120*, 7307–7317. https://doi.org/10.1002/2015JA021661

Lloyd, H. (1842). *Account of the Magnetical Observatory of Dublin and the methods of observation employed there*: The University Press.

Loomis, E. (1861). On the great auroral exhibition of Aug. 28th to Sept. 4th, 1859 and on auroras generally; article 4. *American Journal of Science*, *2*, 32. https://doi.org/10.2475/ajs.s2-32.96.318

Love, J. J., Coïsson, P., & Pulkkinen, A. (1861). Global statistical maps of extreme-event magnetic observatory 1 min first differences in horizontal intensity. *Geophysical Research Letters*, *43*, 4126–4135. https://doi.org/10.1002/2016GL068664

Love, J. J., Hayakawa, H., & Cliver, E. W. (2019). Intensity and impact of the New York railroad superstorm of may 1921. *Space Weather*, *17*, 1281–1292. https://doi.org/10.1029/2019SW002250

Mandea, M., Korte, M., Soloviev, A., & Gvishiani, A. (2010). Alexander von Humboldt's charts of the earth's magnetic field: An assessment based on modern models. *History of Geo- and Space Sciences*, *1*, 63–76. https://doi.org/10.5194/hgss-1-63-2010

Muller, C. (2014). The Carrington solar flares of 1859: Consequences on life. *Origins of Life and Evolution of Biospheres*, *44*, 185–195. https://doi.org/10.1007/s11084-014-9368-3

Nevanlinna, H. (1997). Gauss' h-variometer at the Helsinki Magnetic Observatory 1844-1912. *Journal of Geomagnetism and Geoelectricity*, *49*, 1209–1215.

Nevanlinna, H. (2006). A study on the great geomagnetic storm of 1859: Comparisons with other storms in the 19th century. *Advances in Space Research*, *38*, 180–187. https://doi.org/10.1016/j.asr.2005.07.076

Nevanlinna, H. (2008). On geomagnetic variations during the August-September storms of 1859. *Advances in Space Research*, *42*, 171–180. https://doi.org/10.1016/j.asr.2008.01.002

Nevanlinna, H. (2014). On the early history of the Finnish Meteorological Institute. *Geo- and Space Sciences*, *5*, 75–80. https://doi.org/10.5194/hgss-5-75-2014

Nevanlinna, H., & Häkkinen, L. (2010). Results of Russian geomagnetic observatories in the 19th century: Magnetic activity, 1841-1862. *Annales de Geophysique*, *28*, 917–926. https://doi.org/10.5194/angeo-28-917-2010

Ngwira, C., Pulkkinen, A., Kuznetsova, M., & Glocer, A. (2013a). Modeling extreme "Carrington-type" space weather events using three-dimensional global MHD simulations. *Journal of Geophysical Research: Space Physics*, *119*, 4456–4474. https://doi.org/10.10002/2013JA019661

Ngwira, C., Pulkkinen, A., Leila Mays, M., Kuznetsova, M., Galvin, A. B., Simunac, K., et al. (2013b). Simulation of the 23 July 2012 extreme space weather event: What if this extremely rare CME was earth directed? *Space Weather*, *11*, 671–679. https://doi.org/10.1002/2013SW000990

Ngwira, C., Pulkkinen, A., Wilder, F. D., & Crowley, G. (2013c). Extended study of extreme geoelectric field event scenarios for geomagnetically induced current applications. *Space Weather*, *11*, 121–131. https://doi.org/10.1002/swe.20021

Oughton, E. J., Skelton, A., Horne, R. B., Thomson, A. W. P., & Gaunt, C. T. (2017). Quantifying the daily economic impact of extreme space weather due to failure in electricity transmission infrastructure. *Space Weather*, *15*, 65–83. https://doi.org/10.1002/2016SW001491

Pirjola, R. (2000). Geomagnetically induced currents during magnetic storms. *IEEE Transactions on Plasma Science*, *28*, 1867–1873. https://doi.org/10.1109/27.902215

Pirjola, R. (2003). Effects of space weather on high-latitude ground systems. *Advances in Space Research*, *36*, 2231–2240. https://doi.org/10.1016/j.asr.2003.04.074

Ptitsyna, N., & Altamore, A. (2012). Father Secchi and the first Italian magnetic observatory. *History of Geo- and Space Sciences*, *3*, 33–45. https://doi.org/10.5194/hgss-3-33-2012

Ptitsyna, N. G., Tyasto, M. I., & Altamore, A. (2012). New data on the giant September 1859 magnetic storm: An analysis of Italian and Russian historic observations. In *Proceedings of the 9th Intl Conf. "Problems of Geocosmos", St. Petersburg*.

Pulkkinen, A., Bernabeu, E., Eichner, E., Beggan, C., & Thomson, A. W. (2012). Generation of 100-year geomagnetically induced current scenarios. *Space Weather*, *10*, S04003. https://doi.org/10.1029/2011SW000750

Pulkkinen, A., Lindahl, S., Viljanen, A., & Pirjola, R. (2005). Geomagnetic storm of 29-31 October 2003: Geomagnetically induced currents and their relation to problems in the Swedish high-voltage power transmission system. *Space Weather*, *3*, S08C03. https://doi.org/10.1029/2004SW000123

Pulkkinen, A., Viljanen, A., & Pirjola, R. (2008). Statistics of extreme geomagnetically induced current events. *Space Weather*, *6*, S07001. https://doi.org/10.1029/2008SW000388

Russel, C. T., Luhmann, J. G., & Lu, G. (2001). Nonlinear response of the polar ionosphere to large values of the interplanetary electric field. *Journal of Geophysical Research*, *106*, 18,495–18,504. https://doi.org/10.1029/2001JA900053

Secchi, A. (1859a). Sur les perturbations magnétiques obsèrvées a rome le 2 Septembre 1859, (letter du r.p. Secchi à m. le verrier), comptes rendus, physique du globe, T.XLIX, 458.

Secchi, A. (1859b). Memorie dell'osservatorio del Collegio Romano, Nuovo Serie, Num 1-31.

Shea, M. A., & Smart, D. F. (2006). Compendium of the eight articles on the "Carrington event" attributed to or written by Elias Loomis in the American Journal of Science, 1859-1861. *Advances in Space Research*, *38*, 313–385. https://doi.org/10.2475/ajs.s2-32.96.318

Silverman, S. M. (2006). Comparison of the aurora of September 1/2, 1859 with other great auroras. *Advances in Space Research*, *38*, 136–144. https://doi.org/10.1016/j.asr.2005.03.157

Siscoe, G., Crooker, N. U., & Clauer, C. R. (2006). Dst of the Carrington storm of 1859. *Advances in Space Research*, *38*, 173–179. https://doi.org/10.1016/j.asr.2005.02.102

Stern, D. P. (2002). A millenium of magnetism. *Reviews of Geophysics*, *40*(3), 1007. https://doi.org/10.1029/2000RG000097

Stewart, B. (1861). XXII. On the great magnetic disturbance which extended from August 28 to September 7, 1859, as recorded by photography at the Kew Observatory. *Philosophical Transactions of the Royal Society*, 151. http://doi.org/10.1098/rstl.1861.0023

Takeda, M. (2013). Contribution of wind, conductivity, and geomagnetic main field to the variation in the geomagnetic sq field. *Journal of Geophysical Research: Space Physics*, *118*, 4516–4522. https://doi.org/10.1002/jgra.50386

Thomson, A. W. P., Dawson, E. B., & Reay, S. J. (2011). Quantifying extreme behaviour in geomagnetic activity. *Space Weather*, *9*, S10001. https://doi.org/10.1029/2011SW000696

Tóth, G., Meng, X., Gombosi, T. I., & Rastätter, L. (2014). Predicting the time derivative of local magnetic perturbations. *Journal of Geophysical Research: Space Physics*, *119*, 310–321. https://doi.org/10.1002/2013JA019456

Tsurutani, B. T., Gonzalez, W. D., Lakhina, G. S., & Alex, S. (2003). The extreme magnetic storm of 1-2 September 1859. *Journal of Geophysical Research*, *108*(A7), 1268. https://doi.org/10.1029/2002JA009504

Tyasto, M. I., Ptitsyna, N. G., Veselovsky, I. S., & Yakovchouk, O. S. (2009). Extremely strong geomagnetic storm of September 2-3, 1859, according to the archived data of observations at the Russian network. *Geomagnetism and Aeronomy*, *49*, 153–162. https://doi.org/10.1134/S0016793209020030

Valach, F., Hejda, P., Revallo, M., & Bochnícek, J. (2019). Possible role of auroral oval-related currents in two intense magnetic storms recorded by old mid-latitude observatories Clementinum and Greenwich. *Journal of Space Weather and Space Climate*, *9*, A11. https://doi.org/10.1051/swsc/2019008

Viljanen, A., Myllys, M., & Nevanlinna, H. (2014). Russian geomagnetic recordings in 1850-1862 compared to modern observations. *Journal of Space Weather and Space Climate*, *4*, A11. https://doi.org/10.1051/swsc/2014008

Woodroffe, J. R., Morley, S. K., Jordanova, V. K., Henderson, M. G., Cowee, M. M., & Gjerloev, J. G. (2016). The latitudinal variation of geoelectromagnetic disturbances during large (Dst *leq*-100 nt) geomagnetic storms. *Space Weather*, *14*, 668–681. https://doi.org/10.1002/2016SW001376

Yamazaki, Y., & Maute, A. (2017). Sq and EEJ—A review on the daily variation of the geomagnetic field caused by ionospheric dynamo currents. *Space Science Reviews*, *206*, 299–405. https://doi.org/10.1007/s11214-016-0282-z