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Sporadic and Recurrent Geomagnetic Disturbances in 1859–1860 According to the Archived Data from the Russian Network of Stations

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Abstract—Based on an analysis of the available archived data from the Russian network of geomagnetic stations, it has been indicated that the known event of August–September 1859 was the first and the greatest event in the series of the recurrent geomagnetic storms. Similar series were repeatedly observed in the next years. These series are caused by the processes on the Sun and in the heliosphere related to the superposition of the solar wind flows. The sporadic and regular components in joint activity of the complex, including active regions and coronal holes on the rotating Sun, play the role of the Bartels *M* regions responsible for initiation and development of geomagnetic storms. Neither coronal holes nor active regions can separately explain observations. During interpretation, active regions and coronal holes should be considered as a unified complex.

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1. INTRODUCTION

The beginning of high sporadic activity on the Sun in 1859 was registered in geomagnetic manifestations at the Russian network of stations at the end of August [Tyasto et al., 2009]. In addition to the recent works (see, e.g. [Clauer and Siscoe, 2006]), we performed a retrospective analysis of the available Russian geomagnetic archived data and interpreted the events observed on September 1–5, 1859, in the light of the present-day concepts.

We indicated that the series of several spontaneous eruptions, which followed one another at an interval of several hours to several days, occurred at the end of August–beginning of September, when a new wide and rapidly developing active region appeared at the central solar meridian. One of coronal mass ejections, related (in time) to the famous Carrington flare that occurred at 1120 UT on September 1, 1859, was the strongest event. The effect of this ejection, which reached the Earth the next day, combined with the previous weaker disturbances in the geomagnetic response. As a result, the largest geomagnetic disturbance occurred at 0700–0900 UT on September 2, 1859. This disturbance rapidly started, reached its maximum during 2 h, and weakened more than twice as rapidly as it developed (in an hour). This is the main specific feature of this phenomenon related to peculiar conditions in the heliosphere, which will be considered below in more detail. The remaining features of this geomagnetic storm were similar to those of other such events. During the maximal phase of a geomagnetic disturbance, its current system showed the character of a strongly asymmetric circuit that connected the partial ring current in the equatorial atmosphere to the current jets in the auroral zone, which was shifted at that time to low latitudes south of the system of operated Russian stations. Therefore, the attempts to interpret this event (previously discussed in the literature) using the concepts of the symmetric ring current and the related equatorial *Dst* index [Tsurutani et al., 2003; Siscoe et al., 2006] make the restricted sense in this case. Other researchers [Akasofu and Kamide, 2005] also referred to this situation and drew attention to an excessive character of such estimation for the ring current symmetric part, performed based on the observation at only one station (Kolaba, India). In addition, it is necessary to take into account the induction current within the Earth, field-aligned currents, and magnetopause currents.

The aim of this communication is to demonstrate two new circumstances not considered previously, using the available archived data:

(1) The most powerful group of solar flares, coronal mass ejections, and geomagnetic storms observed at

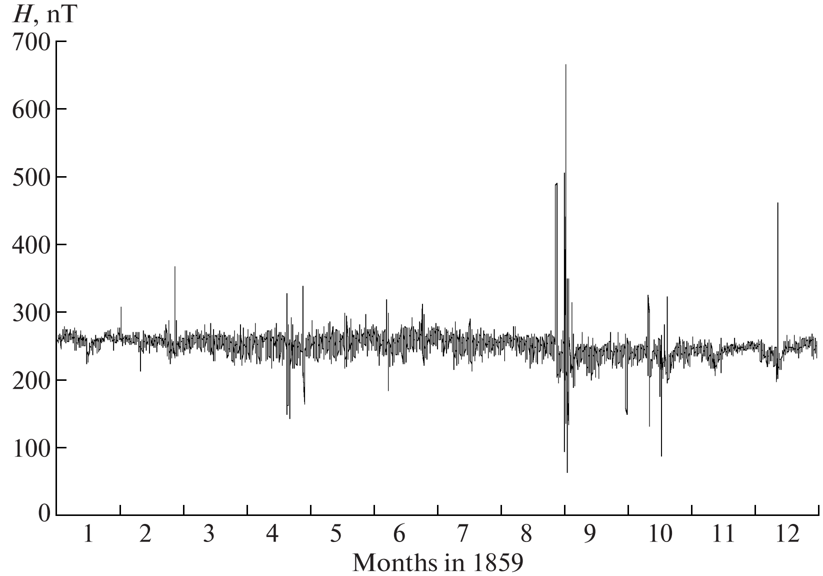

Fig. 1. Horizontal component of the magnetic field (H, nT) measured in St. Petersburg in 1859.

the end of August–beginning of September 1859, was followed by the whole series of weaker disturbances that were confined to the same active longitude on the Sun and were observed during several months up to 1860.

(2) The sporadic and recurrent components of geomagnetic activity, caused by the solar wind streams from the evolved source on the rotating Sun, were superimposed. In this respect, the situation is similar to such events and time intervals in other solar cycles, including cycle 23, when the geomagnetic, heliospheric, and solar data were most ample.

2. SPORADIC AND RECURRENT DISTURBANCES

Speaking about sporadic and recurrent disturbances on the Sun and on the Earth, we should bear in mind two circumstances. First, division of a time series into regular and irregular components (as well as the concept of "regular" and "chaotic" processes) is a slightly conditional mathematical procedure. The concept of regularity is usually related to the existence of a certain algorithm, i.e., a previously known "schedule" and a complete predictability. We assume that everything else belong to something irregular, unpredictable, unknown, or chaotic. However, a more thorough study makes it often possible to move these boundaries aside and to cognize a process more adequately. In such a case, phenomena that seemed to be completely random at first glance can become quite predictable as a result of these efforts and can be subjected to a dynamic and quite deterministic description. Second, we have never observed the entire Sun; therefore, we cannot distinctly separate spatial (longitudinal) dependences from time variations at the same longitude. This uncertainty also remains. Nevertheless, the longitudinal asymmetry of the Sun and its activity is very pronounced in many consistent manifestations in the electromagnetic and corpuscular radiation.

A long time ago it was noted that recurrence does not mean that active processes on the Sun are periodic [Chapman and Bartels, 1940]. A certain alternation is superimposed on this recurrence, which is sometimes traced during very many solar rotations, e.g., 17 rotations from 1929 to 1931. In this case the degree of importance of variations in parameters at a given point of the rotating Sun (e.g., during the period of solar rotation) is unknown. Also long ago, researchers paid attention to the fact that recurrence often has gaps and fading; i.e., the amplitude of recurrent disturbances can complexly depend on time. Therefore, two (rather than one) solar rotations sometimes pass after the first event in the recurrent series.

Figures 1 and 2 present the dependences of the geomagnetic field horizontal (H) component and declination (D) in St. Petersburg in 1859. The field values were counted off from arbitrary zero as was done in the initial tables [*Observations ...,* 1862]. It is clear that large disturbances of August 29–September 3, 1859, were partially spontaneous and partially recurrent since disturbances recurred during several solar rotations in a weaker form. They were confined to approximately the same region of heliolongitudes and appeared at the central meridian on October 18, 1859; November 13, 1859; January 12, 1860; and February 10–22, 1860. A similar pattern was long ago and adequately studied using numerous examples [Chapman and Bartels, 1940].

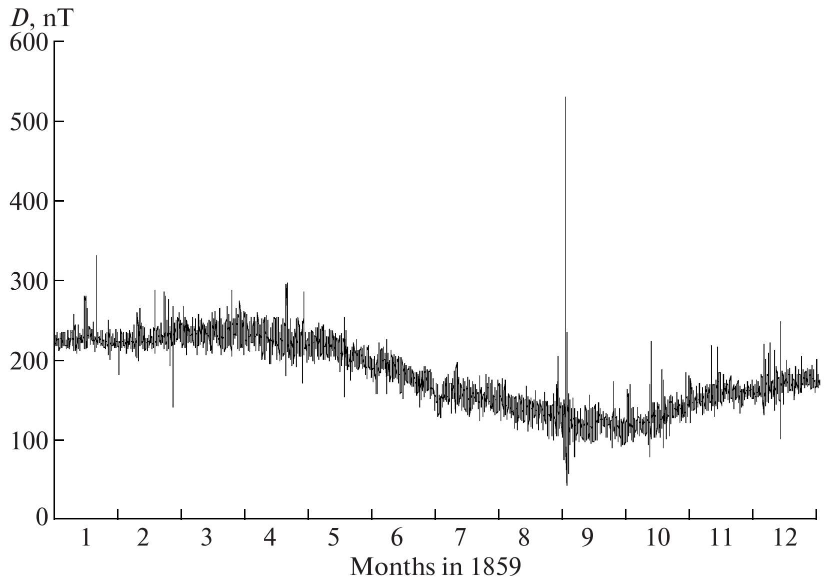

Fig. 2. Magnetic field declination (*D*, nT) measured in St. Petersburg in 1859.

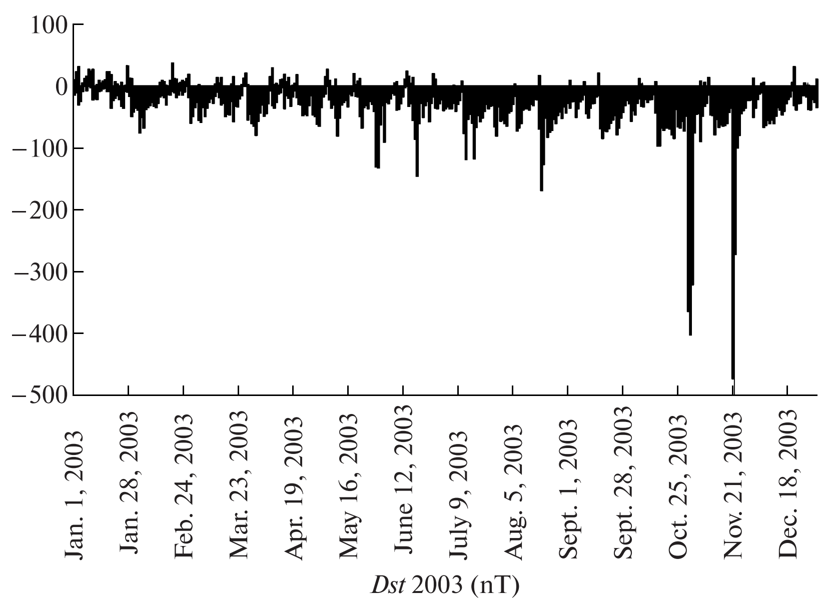

Fig. 3. Daily average values of the *Dst* index (nT) of geomagnetic activity in 2003.

Figures 3 and 4 show the series of similar events that occurred in 2003 and 1999 for the sake of illustration and comparison. It is evident that recurrent disturbances were especially clearly defined in the second half of each year. Spontaneous disturbances are superposed on these disturbances. Slightly similar situation was in 1859–1860, although this situation is represented by the data of direct measurements at one of the midlatitude stations rather than by the *Dst* index (Figs. 1, 2). The years 1859 and 1999 are immediately followed by the maximums of the corresponding (10 and 23) solar cycles.

The relation of a similar pattern to solar sources can be traced in cycle 23 using the APEV complete database (http://dbserv.sinp.msu.ru/apev/fullist.htm). As was noted, the first disturbance in the recurrent series is sometimes the greatest formation, and the remaining disturbances are weaker; however, exceptions to this rule are often observed. This corresponds to a general pattern of fast development of the complex,

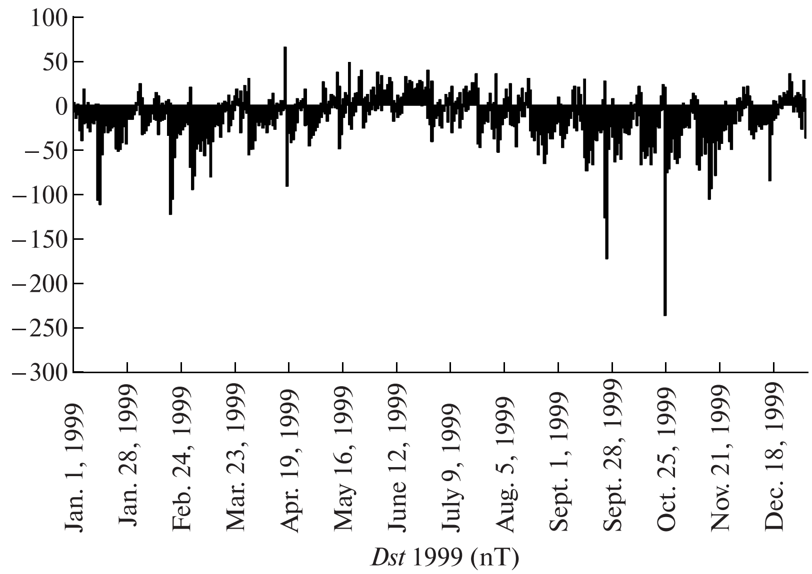

Fig. 4. Daily average values of the *Dst* index (nT) of geomagnetic activity in 1999.

including an active region and coronal hole, and the following slower evolution up to the disappearance of this complex. The strength of induction electric and magnetic fields is maximal during fast development, which is good indication for diagnosing future solar flares using the rate of variations in magnetic flux and its value [Ishkov, 2003]. It is known that the lifetime of active regions is slightly shorter than that of coronal holes and usually accounts for several solar rotations. In this case the role of coronal holes consists in that a high solar wind velocity, which is repeatedly observed from rotation to rotation, is maintained even without spontaneous large-scale processes. The role of active regions consists in the creation of the sporadic component during the formation of related eruptive protuberances and coronal mass ejections. This component is superimposed on the recurrent and more regular structure, first of all, related to high-speed streams from coronal holes. The following solar wind evolution in the heliosphere results in the interaction between fast and slow streams.

We can state that purely empirical concepts of Bartels, who introduced his famous “carpets”, were correct and were developed much ahead that time. However, his description of *M* regions as “restricted regions responsible for geomagnetic disturbances” [Chapman and Bartels, 1940], which was caused by a groundless Chapman’s assumption that a corpuscular flux is narrow, introduced an additional confusion, the consequences of which are still encountered in the literature. A long-standing dispute about active regions and “avoidance cone” as sources of geomagnetic storms is concluded with a compromise and declaration that the question “either or” was put incorrectly in this debate, proceeding from an erroneous concept of a strong and narrow localization of this source on the Sun similarly to the localization of a solar flare. It turned out that this is not the case.

A certain apparent paradox (the fact that great storms are not recurrent) is simultaneously solved. The average angular size of an individual coronal mass ejection is 40°–50° rather than 10° as Chapman formerly assumed for the geoeffective corpuscular flux. This width exceeds 180° for the greatest events [Zhukov and Veselovsky, 2007].

The presented interpretation differs from the available concepts of the physical nature of Bartels *M* regions, according to which the situation is reduced to only high-speed solar wind streams from coronal holes and the following formation of corotating regions during the interaction with a slow wind in the heliosphere (see, e.g. [Cliver, 2006; *Handbook* ..., 2007].

3. CONDITIONS IN THE HELIOSPHERE AND GEOMAGNETIC RESPONSE TO THEM

Development of great geomagnetic storms and their amplitude and duration depend on many parameters and, first of all, on the level of solar activity (including parameters of the solar wind and IMF), season, and time of day. Using the empirical relations established previously, we can try to estimate the conditions in the solar wind that resulted in the geomagnetic storm. The time of disturbance propagation from the Sun to the Earth was about 17.6 h in this case, which corresponds to the average velocity of coronal mass ejection higher than 2000 km/s. The radial thickness of the region across the solar wind disturbed layer can be determined by the coronal mass ejection duration in its source and by the processes of decay and smearing of a convective and wave packet associated with a moving strong inhomogeneity of the plasma and field. This conditional separation roughly corresponds to division into displacement and explosive processes. In the latter case, and precisely the explosive or mixed intermediate process was implemented because the considered intensification and weakening of geomagnetic disturbances were short-term processes that proceeded during about 2–3 h, the thickness of this layer was 0.1–0.2 AU. From this it follows (without particular specification and division into the acoustic and magnetic components) that the effective Mach number is $M \sim 6$–9 for this disturbance.

The extension of the Earth's magnetosphere is mainly controlled by the solar wind dynamic pressure. It is difficult to estimate the solar wind density for this event, although it was indicated that this density in a coronal mass ejection body could be even lower than the average values. Nevertheless, during this stage of studies we assume that the dynamic pressure became much larger than the average statistical values, sometimes, even by an order of magnitude and more mainly due to a five-fold increase in the velocity and local compression near the moving interplanetary shock front. The extension of the magnetosphere rapidly changed in this case, and the compression of the magnetosphere could be dynamic and much larger than the value obtained with the help of a simple estimation using the power-law dependence with index 1/6. In this case a theoretical concept that the magnetosphere is a quasi-equilibrium formation is very far from reality, and the real formation most probably resembles the transient structure of a magnetic cavern around the Earth in the corpuscular flux with a finite lifetime (originating according to the initial concept of Chapman and Ferraro) since the process is rapidly varying.

The intensity and duration of a geomagnetic disturbance first of all depends on the strength of the convective electric field in the solar wind. Three periods of disturbance intensification are distinctly detected during the geomagnetic storm of September 2–3, 1859. Based on the experience in studying similar situation in cycle 23 (see, e.g. [Veselovsky et al., 2004; Yermolaev et al., 2005]), we can absolutely confidently state that three episodes with an intensified southward magnetic field in the heliosphere also took place in this case. The corresponding duration and amplitude of these intensifications can be estimated using the known empirical dependence. An analysis of many geomagnetic storms in cycle 23 made it possible to specify the known simple empirical dependence of the magnetic disturbance amplitude at the equator on the IMF southward component [Akasofu et al., 1985; Veselovsky et al., 2007] in the form $Dst \sim 8.1\ B_z$. This relationship and similar expressions, which are true for the greatest geomagnetic storms accurate to several tens of percent, make it possible to roughly estimate the order of magnitude ($B_z \sim 50$–100 nT in this case) for the main bay-like disturbance (~1100 LT) and to obtain the values that are a factor of 3–5 as small as such values for the remaining two disturbances (~1300 and ~1900 LT).

The probable scenario of the maximal disturbance in the magnetosphere, which should be subsequently verified, is as follows. A short-term drift of a plasma cloud first into and then out of the inner magnetosphere (which was strongly compressed and, therefore, contracted) took place on September 2, 1859, under the action of the external induction electric field with a strength of ~0.1–0.2 V m^{-1} in the solar wind. The strength of the electric field that penetrated into the magnetosphere was apparently decreased by an order of magnitude, as usually happens when IMF is southward. The ring current, which was especially strong in a limited longitudinal interval over the equator, was generated at that time. This current was westward. Precisely this current was mainly responsible for the disturbance of the horizontal component to 1600 nT, which was observed in Colaba (see Fig. 3 in [Tsurutani et al., 2003]). The eastward closure currents at low and middle latitudes generated a magnetic disturbance of the oppositely directed horizontal component of the magnetic field that was observed at the stations in the Russian region [Tyasto et al., 2009]. Since the horizontal component at these stations fell outside the scale of measurements at these stations, it is impossible to speak about the maximal value of this component; we only know that this value was larger than 1000 nT. The contribution of the total electric current, which is connected to the heliosphere in such cases, is unknown. We can assume that this contribution can be quite pronounced [Veselovsky, 2002]. The Chapman–Ferraro, telluric, field-aligned, and magnetospheric currents as well as powerful electromagnetic oscillations were inevitable ingredients. Accelerated charged particles caused auroras. If we accept that the electric field strength on the Earth's surface is 10–20 mV m^{-1} at midlatitudes, taking into account the aforesaid, the induced potential in a telegraph circuit with a length of ~100 km could reach 1–2 kV and could cause breakdown and arcing in narrow spans, which was reported by many observers. Finally, we should emphasize that the geomagnetic disturbance as well as its cause on the Sun and in the heliosphere were actually complex and strong.

4. CONCLUSIONS

An analysis of the available archived data, for the first time, made it possible to detect the recurrent series of geomagnetic disturbances, which continued at least during up to five solar rotations, after strong sporadic disturbances in August–September 1859. Such a phenomenon is not at all extraordinary. A short-duration growth phase and a high intensity of the storm of September 1–2, which included three successive impulses, as well as a short duration of the recovery phase (less than a day) can apparently be qualitatively and semiquantitatively explained by using the known empirical relationships between the governing heliospheric parameters and the magnetospheric response to their variations. This made it possible to retrospectively estimate, specifically, the IMF strength (~50–100 nT), solar wind velocity (higher than ~2000 km/s), and the induction electric field in the solar wind (about 0.1–0.2 V m^{-1}).

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