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Changes in the daily geomagnetic variation during the total solar eclipse of 1 August 2008

A.V. Ladynin [a],*, N.N. Semakov [a], S.Yu. Khomutov [b]

[a] *Novosibirsk State University, ul. Pirogova 2, Novosibirsk, 630090 Russia*
[b] *Altai-Sayan Branch of Geophysical Survey, Siberian Branch of the Russian Academy of Sciences, pr. Akademika Koptyuga 3, Novosibirsk, 630090 Russia*

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Abstract

Geomagnetic measurements during the total solar eclipse of August 1, 2008 in Novosibirsk (Klyuchi Observatory, NVS) and at the Burmistrovo station located on the total eclipse axis revealed eclipse-induced changes against the background of the normal daily variation. The main changes are a decrease in the X (north) component and an increase in the inclination I. Similar changes were recorded at the LZH observatory in China. Analysis of data on the eclipse of August 11, 1999 in Europe failed to unambiguously reveal eclipse effects against intense variations of ionospheric origin which occurred at the same universal time (UT). The geomagnetic effect of the solar eclipse may be due to a decrease in the electron concentration in the ionosphere and the corresponding decrease in the ionospheric current density.

Keywords: geomagnetic field; total solar eclipse; eclipse path; variations of geomagnetic field components

Introduction

Solar eclipses affect the ionosphere at characteristic times of about one hour. Observations of ionospheric perturbations during solar eclipses have shown that the ionosphere responds to solar radiation shielding by the Moon: the decrease in the electron concentration can reach several tens of percent; the ionospheric layers undergo vertical displacements; time delays of tens of minutes are observed between the maximum effect in the ionosphere and the maximum eclipse phase; eclipses frequently generate ionospheric acoustic-gravity waves with periods of 1 hour or more (Babakhanov et al, 2009; Belinskii et al., 2006; Farges et al., 2001; Grigorenko et al, 2008; Jakowski et al., 2008). These effects are significantly different for different ionospheric layers (E, F_1, F_2).

Chapman (1933) proposed a model for the change in the E-layer ionospheric current system (at an altitude of approximately 100 km) that produces the solar quiet daily electromagnetic field variation (Sq variation). A decrease in the electron concentration and conductivity in the E layer should lead to a change in the system of currents and the occurrence of an anomaly in the daily variation curve with an amplitude of up to one third of the field magnitude between the current and nighttime levels.

The main difficulty in identifying eclipse effects on the geomagnetic field is due to the fact that measurement results typically contain many geomagnetic variations not related to the eclipse. In addition, the expected changes are small, about a few to a few tens of nanoteslas.

One of the first studies of eclipse effects on the geomagnetic field during the total solar eclipse of 12 November 1966 in Peru recorded an anomaly in the horizontal component with an amplitude of 30 nT, which is consistent in magnitude and sign with the Chapman model (Bomke et al., 1967). Researchers noted an about 2 min delay of the extremum in the geomagnetic field relative to the time of maximum eclipse. Less reliable results were obtained during the eclipse of July 11, 1991 in Costa Rica—the presumable effect of the H horizontal component was 5 nT but the sign of the anomaly was opposite to that predicted by the Chapman model (Brenes et al., 1993). During the solar eclipse of October 23, 1976 in Australia, measurements of the magnetic declination at three stations distributed along the path of totality revealed magnetic anomalies of amplitude up to 5 nT at times close to the maximum eclipse times (Lilley and Woods, 1977). During the total eclipse of October 24, 1995 in Vietnam, measurements at three temporary stations under the favorable conditions of

* Corresponding author.
E-mail address: avlad@academ.org (A.V. Ladynin)

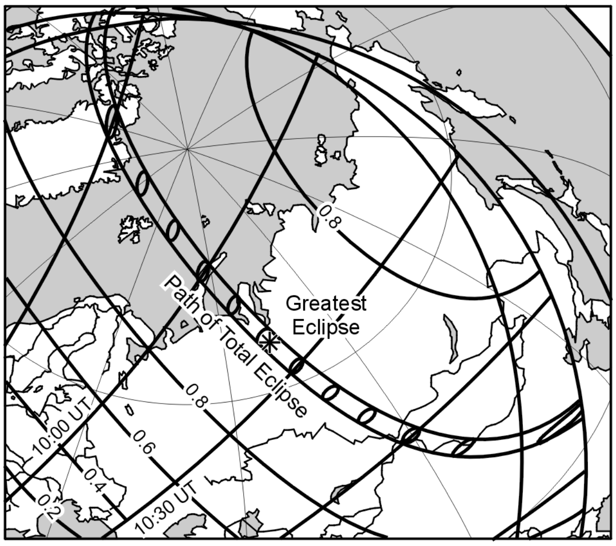

Fig. 1. Totality path of the eclipse of August 1, 2008 from (Espenak and Anderson, 1999, 2008).

proximity to the magnetic equator and the high position of the Sun revealed a change in the horizontal component with an amplitude of several tens of nanoteslas in proportion to the daily *Sq* variation (Nguen Thi Kim Thoa et al., 1997).

The total solar eclipse of August 11, 1999 in Europe was productive for the study of its geophysical manifestations because the shadow passed over an area where there is a dense network of magnetic observatories (MOs), and, in addition, a number of temporary stations were installed for the period of the eclipse. Strestik (2001) noted an increase of 10 nT in the *Y* component during the eclipse and a decrease in the *X* component of 5 nT from data of four observatories. However, the first anomaly is in agreement with the Chapman model, whereas the second is in opposition to it.

However, Korte et al. (2001) question the findings of the eclipse effect on the geomagnetic field in Europe. The reasons for this are the absence of correlations between the geomagnetic variations predicted by the *Sq* current system model for the eclipse time and control days and the real data, and the absence of geomagnetic field anomalies in the corresponding current structures in the Southern Hemisphere. Hvozdara and Prigancova (2002) performed model calculations of geomagnetic effects on the surface from conductivity disturbances in the E layer over Europe.

It was shown that calculated and experimental variations of the geomagnetic field during the eclipse of August 11, 1999 were similar for the Y component, and the variation of the *X* component was much smaller and its sign was opposite to that predicted by the Chapman model.

Malin et al. (2000) investigated geomagnetic field variations in Turkey and at four observatories in Europe and found positive anomalies in the declination *D* (and the Y (east) component with an amplitude of up to 15 nT) during the maximum eclipse phase. Effects of the horizontal and vertical components were not observed. As a continuation of this work, Ozcan and Aydogdu (2004) calculated variations in the *E*-layer ionospheric current over Turkey and showed that the model results were qualitatively consistent with experimental data (Malin et al., 2000).

An analysis of ionospheric and geomagnetic data during the eclipse of August 11, 1999 in Europe is given by Curto et al., (2006). The authors use data from a network of magnetic observatories and analyze variations of the *Y* component, which has the regular *Sq* variation at mid-latitudes. Estimates of the effect obtained from measurement data are close to the expected results: the positive anomaly in the Y component has an amplitude of several nanoteslas and is then used to calculate the ionospheric effect.

These results of studying the effect of solar eclipses on the geomagnetic field show that the problem remains open. It is generally recognized that geomagnetic anomalies during eclipses result from ionospheric disturbances. However, calculations for models of the equivalent *Sq* current system in the ionospheric *E* layer have been made only for the eclipse of August 11, 1999 in Europe. Therefore, performing geomagnetic measurements during eclipses remains an urgent problem: new data are necessary for understanding ionospheric processes.

The present study investigates changes in the daily variation of the geomagnetic field during the total solar eclipse of August 1, 2008. The eclipse totality path (Fig. 1) began in northern Canada and extended in a roughly east-west direction across the polar region. In Siberia, it passed in a roughly north-south direction through Novosibirsk, where there is the Klyuchi magnetic observatory (NVS), and then in a roughly east-west direction to China, where it ended. In Novosibirsk, the eclipse began at 09:41:02 UT; the maximum phase began at 10:43:50 and lasted 2 min 20 sec until 10:46:10 at a solar elevation angle of 30°; the eclipse ended at 11:45:03 UT.

Along with finding changes in daily geomagnetic variations near Novosibirsk under favorable conditions of a high position of the Sun, we analyzed data from four MOs where the eclipse was almost total but the sun was low on the horizon: at Cambridge Bay (CBB), at Resolute (RES) in the northeast of Canada and Thule (THL) in north-western Greenland at sunrise, and at Lanzhou (LZH) in China at sunset. At both the LZH and NVS magnetic observatories, the following changes were detected in the geomagnetic field components during the eclipse of 2008: a decrease in the *X* (north) component and an increase in the inclination *I*.

From the data obtained at the magnetic observatories of Europe during the eclipse of August 11, 1999, it was not possible to unambiguously identify eclipse effects in geomagnetic field variations. The reason for this is intense geomagnetic bay disturbances which occur at the same universal time.

The cause of the effect of the eclipse of August 1, 2008 observed in Novosibirsk (NVS) and Lanzhou (LZH) during quiet geomagnetic field could be a reduction in the ionospheric current density due to a sharp decrease in the electron concentration and a local decrease in the north component of the magnetic induction of ionospheric currents.

Results of observations in Novosibirsk

At the Klyuchi geophysical observatory (NVS, coordinates 54°50′ N, 83°14′ E), the *X*, *Y*, and *Z* components of the geomagnetic field are continuously recorded by a LEMI-008 fluxgate magnetometer at a frequency of 1 Hz. The magnitude of the magnetic flux density vector (*F*) is measured at an interval of 5 s by an Overhauser (OVH) proton magnetometer. The network of such observatories is rather sparse, and it is reasonable to use temporary stations to detect eclipse effects. We installed such a station on the axis of the maximum eclipse path in the village of Burmistrovo (54°51′ N, 82°45′ E). Here three-day measurements were performed using three OVH magnetometers at sampling intervals of 1 and 5 min and a system of vector measurements (*D* and *I* were measured by fluxgate theodolites, and *F* was measured by an OVH magnetometer) at a sampling interval of 15 min.

Figure 2 shows the daily curves (daily variations) of the magnitude of the flux density vector *F* measured on August 1, 2008 at the NVS MO and Burmistrovo. Curves of *F* for the next day are also given for comparison. It is evident from these data that on August 2, the geomagnetic field was quiet, and on August 1, it was slightly disturbed.

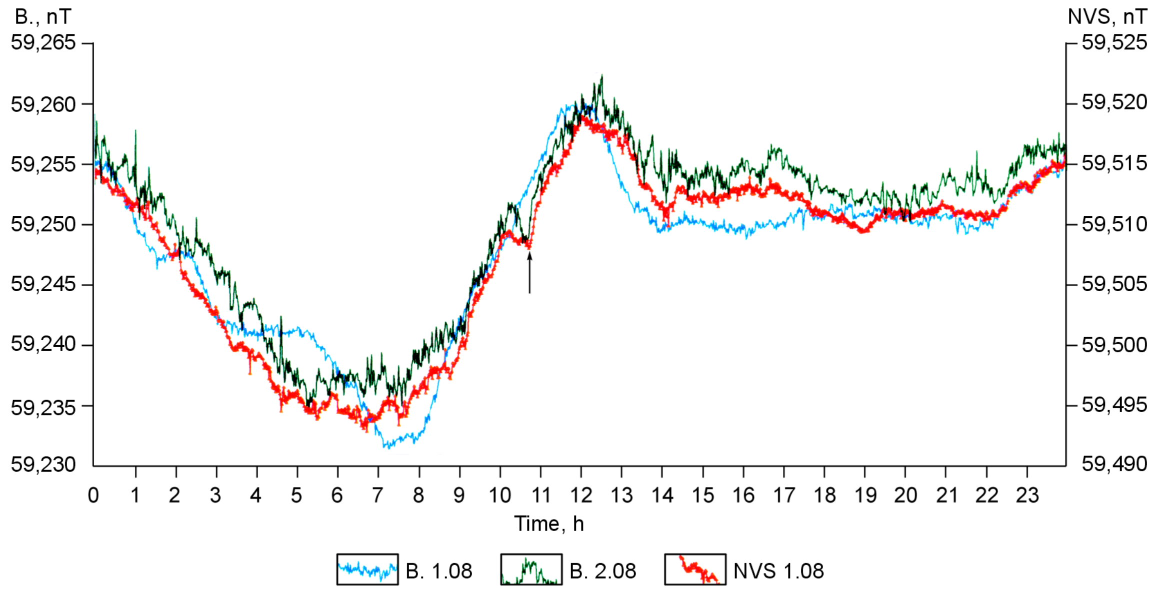

Fig. 2. Daily variation of F from measurements at Burmistrovo on August 1 and 2 (left scale) and at the Klyuchi observatory (NVS) on August 1 (right scale). Arrow shows the maximum eclipse time.

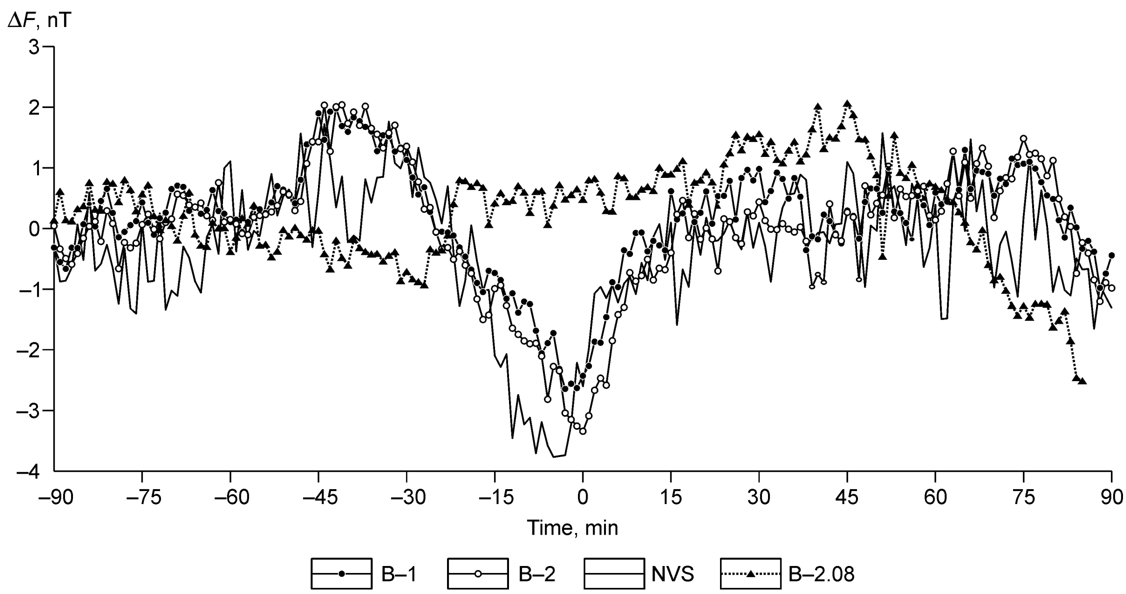

Fig. 3. Variation of F during a three-hour interval centered at the time of maximum eclipse on August 1, 2008. B-1 and B-2, data from two OVH magnetometers at Burmistrovo on August 1; NVS, record of an OVH magnetometer at the Klyuchi MO; B2.08, data of an OVH magnetometer at Burmistrovo, August 2.

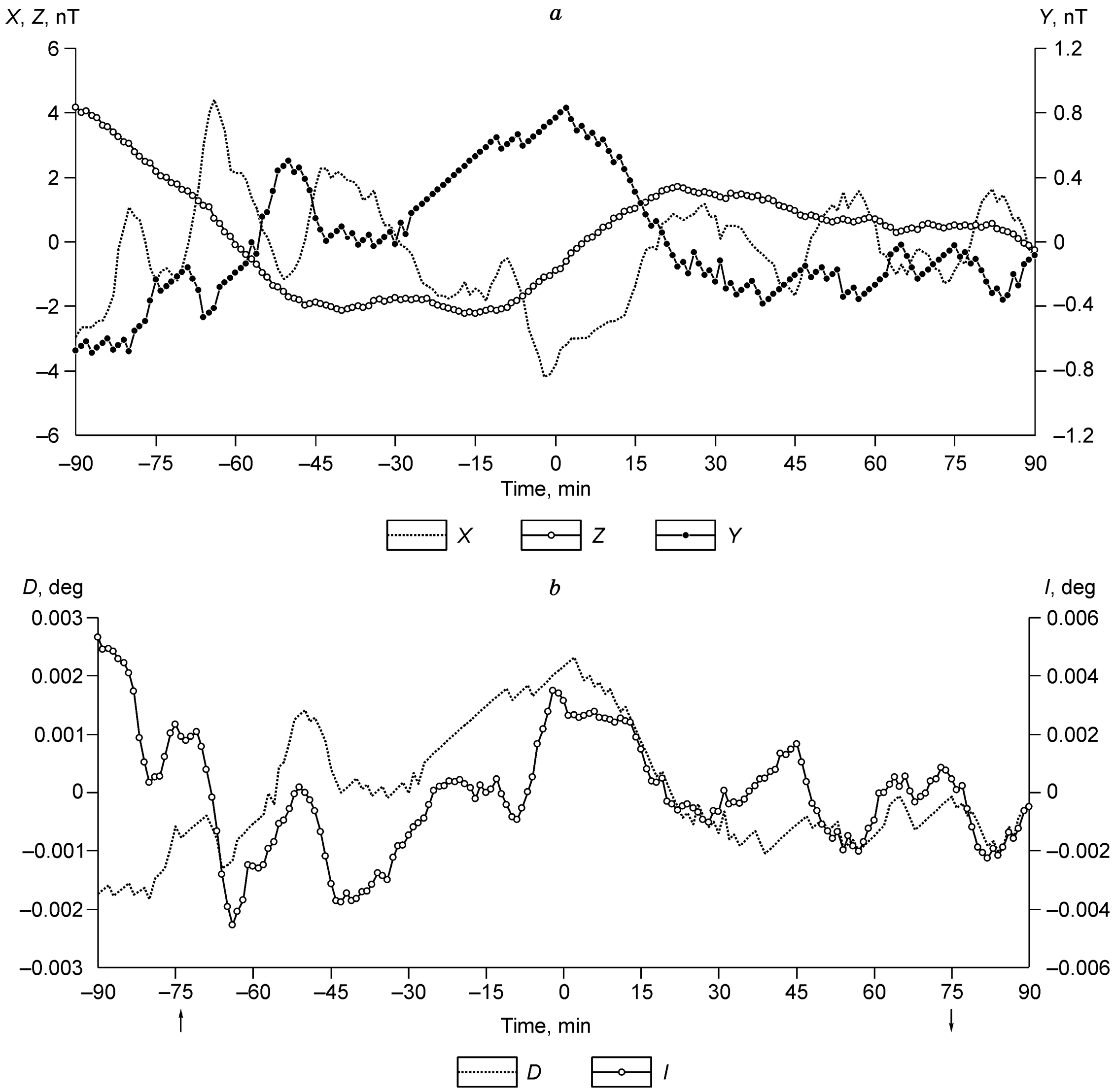

Fig. 4. Variations of the geomagnetic field components in the NVS MO during the eclipse of August 1, 2008. *a*, force components; *b*, angular components.

The daily variation curves of *F* (see Fig. 2) show that during totality, the magnetic flux density decreased by 4 nT according to measurements at Burmistrovo and by 5 nT according to the NVS MO. This anomaly occurs against the background of the almost linear trend from 07:30 to 12:30 UT. For a better visualization of this feature of *F*, we chose to analyze an interval of 3 h centered at the time of maximum eclipse 10:45 UT and eliminated the linear trend. The moments of the maximum eclipse phase are taken from data (Espenak and Anderson, 1999, 2008).

Figure 3 shows the variations in the flux density magnitude during a three-hour interval obtained 01.08.2008 at the NVS observatory and by two magnetometers at Burmistrovo (B-1 and B-2) and OVH magnetometer data obtained 02.08.2008 at Burmistrovo (B. 2.08). The elimination of the linear trend has made it possible to plot the curves on the same scale.

For the data from Burmistrovo, the measurement errors of F in three-hour samples were estimated from the difference of simultaneously operating OVH magnetometers, and for the data from the NVS MO, they were estimated by comparing the values of F from the direct measurements (denoted by *F*) and the geometric sum of the values of the components (T_k) from records of three-component magnetographs $T_k = \sqrt{X^2 + Y^2 + Z^2}$. The standard deviation of *F* over the three-hour observation interval is ± 0.17 nT at Burmistrovo (B-1 and B-2) and ± 0.24 nT (*F* and *Tk*) at the NVS MO. The measurement error, as we see, is an order of magnitude smaller than the changes in the geomagnetic field detected during the eclipse.

The three-component (*X*, *Y*, *Z*) measurements at the NVS MO were used to calculate the other components of the geomagnetic field—*H*, T_k, *D*, *I*. Their variations during the eclipse are shown in Fig. 4 (the maximum phase 0 on the timeline).

During the eclipse, one can see distinct maxima of the *Y*, *D*, and *I* components and minima of *X* and *Z* (and *H* and

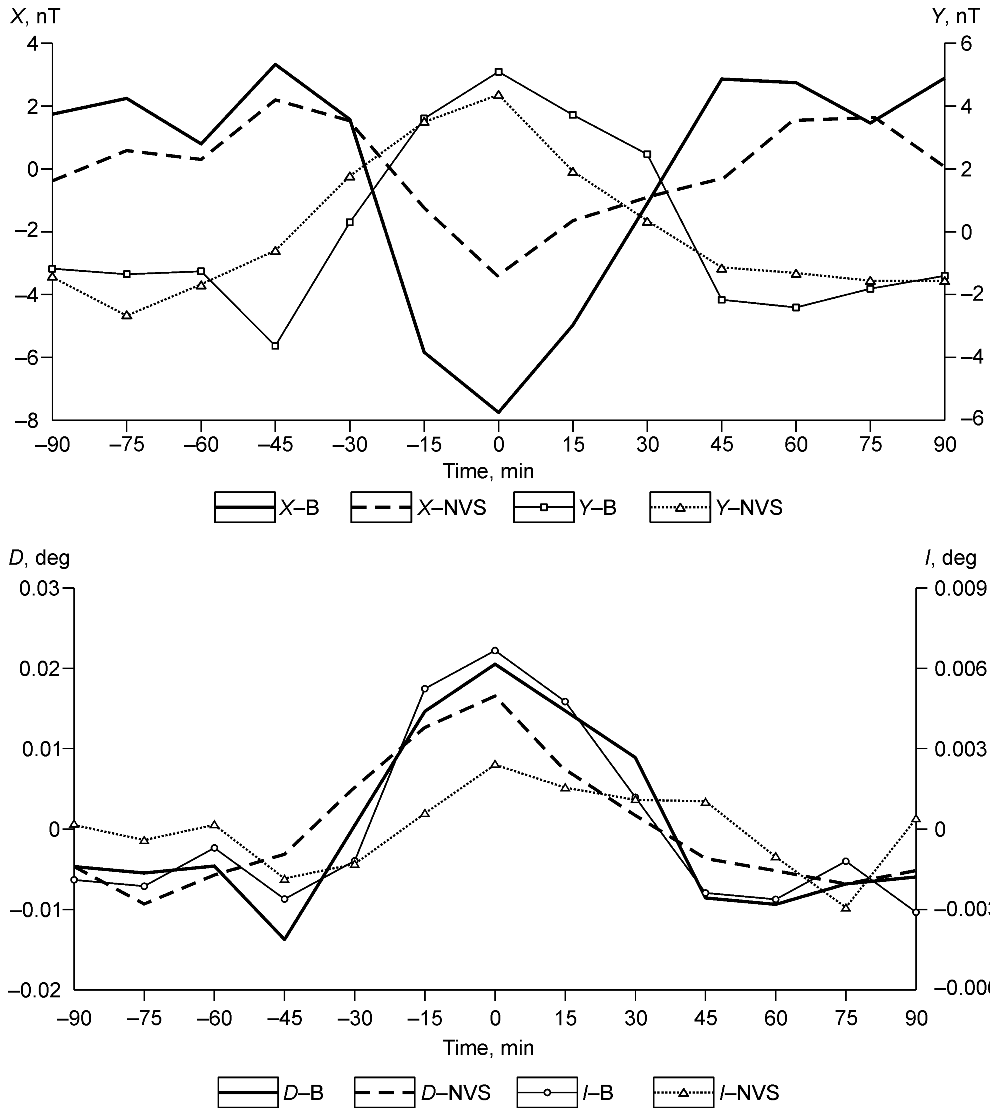

Fig. 5. Variations of the geomagnetic field components during the eclipse of August 1, 2008 in Novosibirsk.

F; these curves are not shown due to their proximity to the curves of X and *Z*, respectively). The values of the extreme changes are –6 nT for *X*, 1.2 nT for *Y*; 0.03° for *D*; 0.006° for in I. It is seen that the geomagnetic field was turbulent, but the effect of the eclipse observed the similar (–53 and 73 min).

The three-component measurements at Burmistrovo (at a sampling interval of 15 min)

show a similar pattern. Figure 5 gives these measurement data in comparison with a sample of the same quantities from the NVS MO 443 with a step of 15 min. The values of *X* and *H* are given after deduction of average daily values, and the values of *F*, *Y*, *D*, and *I* do not include the linear trend during 3 h.

From the data of three-component measurements at Burmistrovo, one can confidently identify maximum values at the time of the eclipse for the *Y* component (9 nT) , declination *D* (about 0.03°), and inclination I (about 0.09°) and a minimum for *X* (–11 nT). In the data from the NVS MO, the extrema of *I* and *X* have somewhat smaller amplitudes.

Geomagnetic variations at other observatories along the 2008 eclipse path

The only observatory lying in the path of totality in its eastern part was the LZH MO (Lanzhou, China; coordinates 36°05′ N, 103°14′ E).

According to the data of the LZH MO, where the eclipse occurred before sunset, *F* decreased by 8, *X* by 13, and *Z* by 2 nT (Fig. 6, *a*). The *Y* component had an overall increase of 6 nT with a decrease of 1 nT before the main phase of the eclipse and an increase of 3 nT after it. The shape of the curve of *D* is similar (see Fig. 6, *b*) with an overall increase

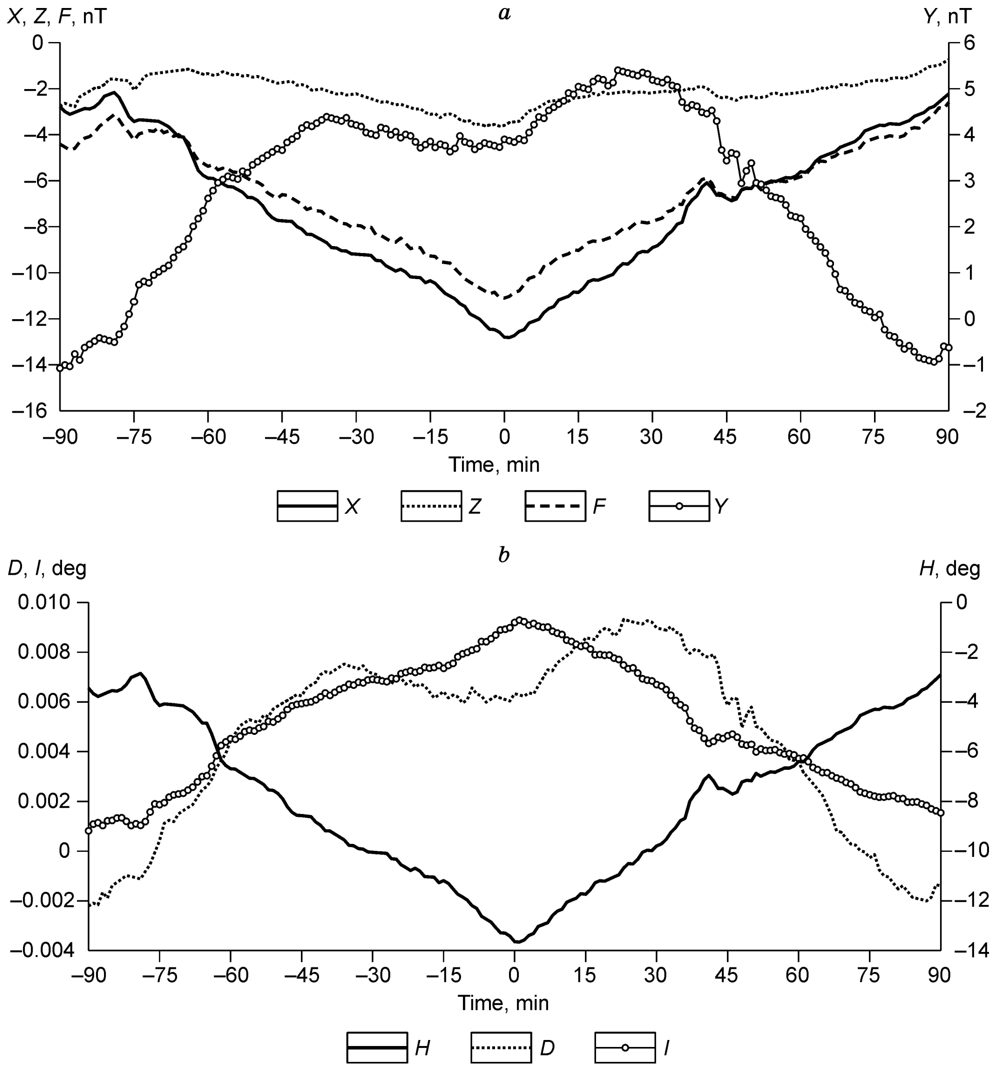

Fig. 6. Variations of the geomagnetic field components at the LZH MO during the solar eclipse of August 1, 2008. *a* and *b*, for explanation see the text.

of 0.007°. The inclination *I* varied in antiphase with the *H* horizontal component: *I* increased by 0.008°, while *H* decreased by 10 nT. These changes in the field are similar to the corresponding variations in the data of the NVS MO.

On the day of the eclipse, the geomagnetic field near the pole (CBB MO, RES, and THL) was unstable. We give a plot of the *X*, *Y*, and *Z* components with the excluded linear trend in a 3 h interval (Fig. 7) at the Thule observatory (THL) in Greenland. Here one can see that the decrease in *X* and the increase in *Y* are similar to those observed at other MOs, but they are superimposed on complex oscillations of a different nature. The combination of the two minima of *Z* with an amplitude of 30–36 nT with the maximum between them during totality is probably just a coincidence of the eclipse with bay variations of the *Z* (and *F*) components of the geomagnetic field. The data from the Cambridge Bay (CBB) and Resolute (RES) MOs in Canada do not show noticeable effects during the eclipse, probably due to significant disturbances of the field, a low position of the sun above the horizon, and small values of the *X* component in the circumpolar region.

Regular changes of the geomagnetic field at the NVS and LZH observatories during the total solar eclipse of August 1, 2008 are as follows:

1) a decrease in the *X* (north) component of the geomagnetic field and the horizontal H component and an increase in the inclination *I* in antiphase with *H*;

2) an increase in the declination *D* and the *Y* (east) component with different ratios of the quantities at different MO;

3) a decrease in F and a less pronounced decrease in *Z*; the latter is not always indicated in plots of *F* and *Z* from magnetic observatories at the INTERMAGNET site.

For comparison with the results of the NVS and LZH MOs for August 1, 2008, we invoke data of European magnetic observatories on the total solar eclipse of August 11, 1999, which, as noted above, have been reported in are many publications.

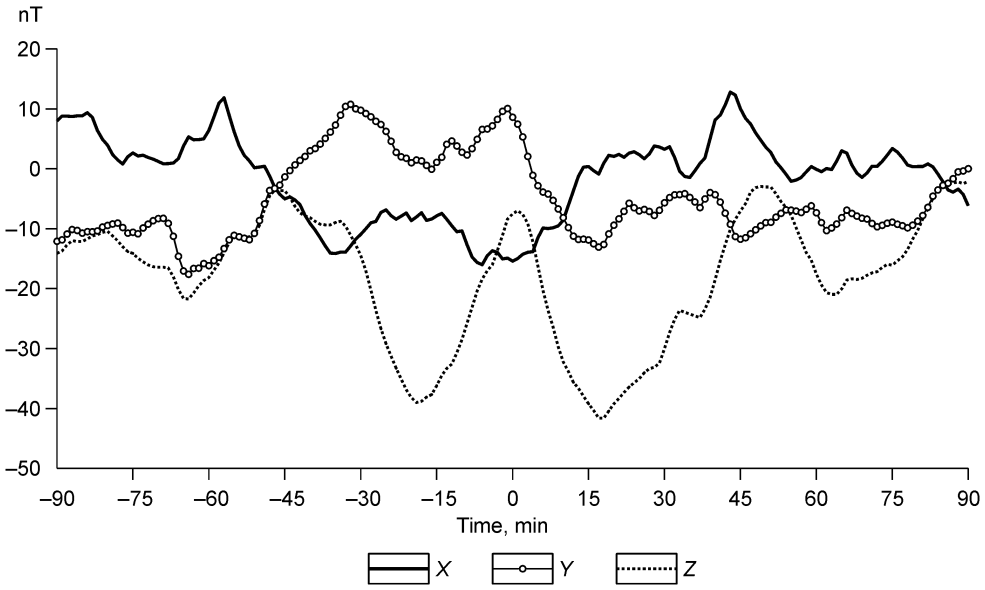

Fig. 7. Variation of the geomagnetic field at the THL MO (Greenland) during the eclipse of August 1, 2008.

Geomagnetic variations during the eclipse of August 11, 1999 in Europe

An analysis of the changes in the geomagnetic field components in a compact group of FUR, NCK, and THY MOs in the path of totality performed using the method described above did not give unambiguous results.

For these three MOs, Fig. 8 shows curves of *H* and *I* in one-hour interval relative to the time of totality in each of the MOs. The values of the components are given relative to the daily average values. One can see the antiphase distribution of the extrema of *H* (minimum) and I (maximum) over these observatories, but the confinement of these extrema to the total eclipse phase (0 on the timeline) is not observed. The effects in the geomagnetic field are shifted relative to the time of totality at these MOs.

Table 1 lists the coordinates of the magnetic observatories, the time of maximum eclipse (UT), the shift of the extrema of *H* (and *X* and *I*; they are synchronous) relative to the time of maximum eclipse.

The fact that the sum of the values in last two columns of the table is equal to 10 h 46 min implies that the extrema of H and I occur at the same UT, and. hence, there is no reason to associate them with the eclipse. This can be seen in Fig. 9, which shows the variations of H in an 1.5 h interval from the mean values in this interval. Arrows show the times of totality in each of the five MOs.

The geomagnetic field of 11 August, 1999 in Europe was quite disturbed. A variation similar to the change in the field during the eclipse in Novosibirsk was recorded at 10:46, which agrees with the middle time (UT) of the eclipse at the three central MOs and is close to the middle of the eclipse at the five observatories. In the averaged variations of the various field components from the three central MOs, the geomagnetic effects of the eclipse are similar to the effects of the eclipse of August 1, 2008 at the NVS and LZH; they have identical distribution patterns of the signs of the extrema of the components during totality, i.e., the maxima of *Y*, *I*, and *D* and the minimum *X* and *H* (these plots are not given).

Thus, from the data on the eclipse of August 11, 1999 in Europe, it is difficult to draw an unambiguous conclusion on the geomagnetic effects of the eclipse. Two versions are possible:

1. The variation at 10 h 46 min is a geomagnetic bay disturbance which occurred at the same UT at all MOs and coincided with the eclipse time in central Europe. The parameters of this variation are similar to the effects of the 2008 eclipse in Asia.

2. This is an effect of the eclipse but it is regularly shifted relative to the moment of the eclipse at each MO.

Table 1. Coordinates of MO and the time of totality on 8.11.1999

MO index	Latitude, deg	Longitude, deg	UT of eclipse, hours:min	Shift, min
FUR	48.165	11.277	10:38	8
NCK	47.630	16.720	10:48	–2
THY	46.900	17.893	10:50	–4

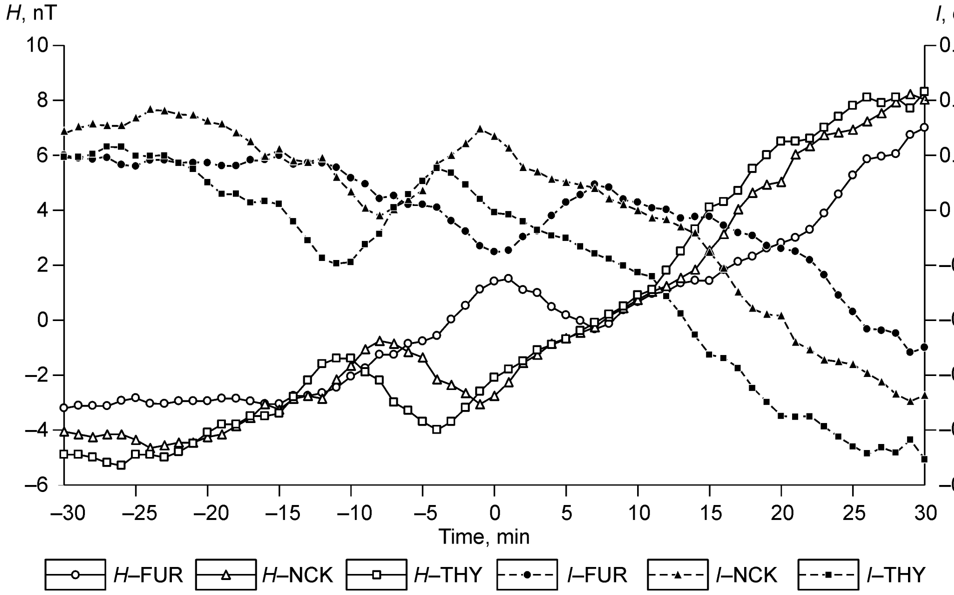

Fig. 8. Shift of the effect extrema relative to the time of totality on August 11, 1999 in three European MOs.

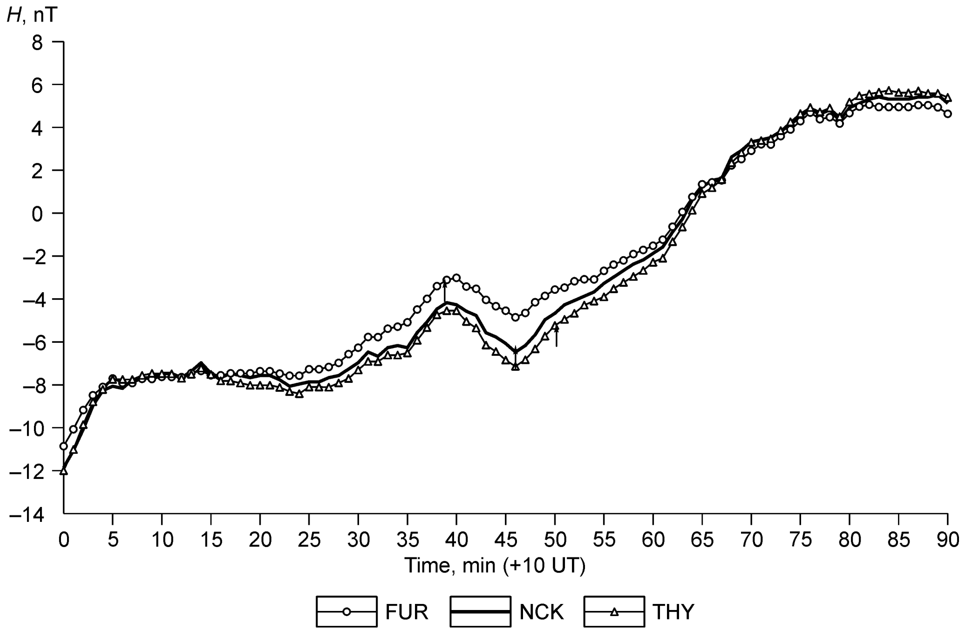

Fig. 9. Changes in the horizontal component H of the geomagnetic field from 10:00 to 11:30 ut on August 11, 1999 in the three magnetic observatories in Europe. Arrows - the maximum eclipse time at each MO.

Discussion

The following changes in the geomagnetic field components during the total solar eclipse of August 1, 2008 were found at observatories in Asia:

(1) a decrease in the *X* (north) component of the geomagnetic field and the horizontal *H* component; an increase in the inclination *I* in antiphase with X and *H*;

(2) an increase in the declination *D* and the *Y* (east) component;

(3) a decrease in *F* and a less pronounced decrease in *Z*.

Of the above-mentioned changes, the decrease in the north component of the geomagnetic field is the most significant and reliable.

During the eclipse of August 11, 1999 in Europe, the effect of the eclipse was not unambiguously identified due to disturbance of the geomagnetic field. Possibly, the eclipse time coincided with a geomagnetic bay disturbance which occurred at the same UT at all observatories. If this variation is interpreted as an effect of the eclipse, there is a shift in the extrema relative to the time of maximum eclipse, which changes linearly with the MO longitude along the path of totality from 8 min at the FUR MO to –4 min at the THY MO, i.e., in the western part of the European path of the eclipse, its geomagnetic effect was delayed relative to the time of totality, and in the eastern part, it occurred before totality.

These effects can be attributed to a 70% decrease in the solar ionizing radiation flux and the electron concentration in the ionosphere during the eclipse, as is shown in (Davis et al., 2000). These disturbances in the ionosphere can lead to a corresponding decrease in the current density in the lower ionosphere and a local decrease in the north component of the magnetic induction of this current.

The ionospheric changes observed during the 1999 eclipse were diverse and similar to those observed in other solar eclipses (Le at al., 2008): these are changes in the electron concentration, temperature at different altitudes, circulation conditions in the upper atmosphere, etc. In the lower E layer at an altitude of ~100 km, nearly night conditions were observed. In the F_1 (~200 km) and F_2 (~300 km) layers with higher electron concentrations, the electron concentration was decreased to 0.3 of its normal value, and this decrease occurred with a delay of 15 min in the F_1 layer and 30 min in the F_2 layer. This makes it possible to associate the delay of the geomagnetic effect of the eclipse in Western Europe with this factor.

The totality path had a roughly east–west direction. Prevailing winds in the upper ionosphere are west and north-west; in the west of Europe, a region of high wind speeds exceeding 200 m/s was recorded on this day (Eclipse effects ..., 2003). The ionosphere depleted in electrons could be moved by this wind to the east before the onset of the eclipse there, resulting in the geomagnetic effect occurring before the time of totality at the THY MO.

Conclusions

Changes were found in the daily variation of the geomagnetic field during the total solar eclipse of August 1, 2008 in Asia (Novosibirsk, Lanzhou). The main geomagnetic effects of the eclipse are a decrease of 8–10 nT in the X (north) component and an increase of 0.004–0.009° in the inclination. Detection of these effects was possible because of the relatively quiet geomagnetic field on the day of the eclipse.

It was shown that the eclipse effect can be detected by observations at temporary stations with continuous recording or by discrete observations with a step of 15 min, as is customary in the PVC system (Ladynin et al, 2006).

Analysis of data from European observatories during the eclipse of August 11, 1999, when the geomagnetic field was disturbed, failed to unambiguously identify eclipse effects against the background of intense ionospheric variations occurring at the same UT. There are two possible explanations for the changes in the daily variation of the geomagnetic field during this eclipse in Europe.

1. The variation at 10 h 46 min is a geomagnetic bay disturbance which occurred at the same UT at all MOs and coincided with the eclipse time in central Europe. This explanation is supported by the fact that a few more anomalies occurred at the same UT at all the observatories on the day of the eclipse.

2. This is an effect of the eclipse but it is regularly shifted relative to the eclipse time at each MO. Arguments in favor of this explanation are as follows: the parameters of the variation are similar to the effects of the eclipse of August 1, 2008 in Asia; the shift of the eclipse effect relative to the time of totality can be explained consistently.

The results presented in this article were obtained at HAD, FUR, NCK, THY, and SUA magnetic observatories in 1999 and NVS, LZH, THL, CBB, and RES observatories in 2008, We thank the staff of these observatories and INTERMAGNET for the providing high quality data via http://www.intermagnet.org.

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