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GEOMAGNETIC EFFECTS OF A METEOR EXPLOSION OVER THE VERKHNETULOMSKY RESERVOIR ON DECEMBER 19, 2014

S.M. Cherniakov

Polar Geophysical Institute, Murmansk, Russia; e-mail: *smcherniakov@gmail.com*

Abstract. The geomagnetic effects of a meteor explosion on December 19, 2014 at high latitudes over the Kola Peninsula, Russia are considered. The response of the geomagnetic field was considered based on data from the magnetometer (Loparskaya Geophysical Observatory of the Polar Geophysical Institute) and stations of the International Monitor for Auroral Geomagnetic Effects (IMAGE). It was shown that the meteor explosion caused changes in the values of the geomagnetic field components. It is assumed that the sharp changes are caused by the impact of the shock wave from the explosion on the auroral electrojets, and the subsequent wave-like variations of the components are caused by the modulation of ionospheric currents in the dynamo region of the ionosphere by acoustic-gravity waves. For the first time, it was suggested that sudden changes in the geomagnetic field are caused by the impact of the shock wave from the meteor explosion on auroral electrojets.

Introduction. The processes that occur in the Earth's atmosphere during the passage of meteoroids, as well as the generation and propagation of waves recorded after the invasion of celestial bodies into the atmosphere, are of interest and are constantly being studied [*Edwards et al.*, 2006; *Glazachev et al.*, 2021; *Spivak and Riabova*, 2019]. The invasion of meteoroids of various scales occurs constantly, however, the response of the geomagnetic field is still not fully understood.

The flights of meteoroids are accompanied by various processes: heating, combustion and destruction of the meteoroid, the generation of various types of waves, including shock, acoustic-gravity and slow magnetohydrodynamic waves, as well as the ionosphere and the geomagnetic field disturbances. The study of the reaction of the geomagnetic field to the intrusion of meteoroids makes it possible to classify their response to this phenomenon and assess the degree of their changes in various cases.

Observation methods and explosion location. On December 19, 2014 a trace of a meteor fall was recorded using optical monitoring of the state of the environment (all-sky cameras of the Polar Geophysical Institute in the Verkhnetulomsky Observatory, 68.60° N, 31.75° E, and the city of Apatity, 67.6° N, 33.41° E). The destruction of this meteor over the Kola Peninsula at 19:03:07 UT was followed by the bright flash (68.6° N, 31.1° E).

The response of the geomagnetic field was considered using the geomagnetic field components H, D and Z of the magnetometer of the Loparskaya Geophysical Observatory of the Polar Geophysical Institute (68.25° N, 33.08° E). Relative to the location of the meteor explosion, the Observatory was at a distance of about 90 km to the east. A description of the magnetometer and the obtained data can be found on the Polar Geophysical Institute website. According to data from the Observatory, planetary indices Kp and data from the GOES satellite, the geomagnetic situation on December 19 during the meteor explosion was quiet.

Data processing was performed using the MATLAB programming language application package. To define periodic components, a digital Cauer elliptic bandpass filter was used. Its feature is a steep decline in the amplitude response, which allows for more effective frequency separation than when using other linear filters. The cutting periods were specified in each considered case. For wavelet analysis of the spectral components of the data, the Morlet wavelet of the MATLAB application package was used.

Geomagnetic effects of the meteor explosion. The geomagnetic field is an indicator of many processes occurring on the Earth, in the surrounding space and on the Sun. Changes in the geomagnetic field are caused by natural causes: solar flares, processes in the ionosphere and the magnetosphere of the Earth, as well as various artificial phenomena: powerful explosions of chemical and nuclear weapons, missile launches and flights, modification of the ionosphere by powerful radio waves, etc. An extensive network of magnetic stations, located throughout the globe, allows continuous and high-precision measurements of variations in the geomagnetic field. Thus, this makes it possible to monitor simply and effectively processes in the near-Earth plasma caused by the influence of various sources on it, including the fall of celestial bodies.

Geomagnetic field variations are the superposition of various geomagnetic field disturbances. Their identification is sometimes quite a difficult task. The task is easier if the parameters of the phenomenon that caused the disturbance are known (place, time, characteristics, etc.) However, the response of the geomagnetic field to various natural and artificial processes has not been fully studied. All this also applies to those flying into the Earth's atmosphere of meteoroids, the flight of which is accompanied by various processes: heating, combustion and destruction of the meteoroid, the generation of various types of waves, including shock, slow magnetohydrodynamic and acoustic-gravity waves, as well as disturbances of the geomagnetic field [*Bronshten*, 1981; *Catastropjic*, 2005].

The first works devoted to the influence of flights and explosions of cosmic bodies in the Earth's atmosphere on the geomagnetic field examined its reaction to the explosion of the Tunguska meteorite on June 30, 1908. For many years and to this day, the Tunguska catastrophe has attracted the attention of researchers, including the impact of the explosion on the Earth's magnetic field [*Bronshten*, 2002; *Ivanov*, 1961; *Rakhmatulin et al.*; 2013; *Shaidurov*, 2015].

Since the flights of meteoroids are recorded by environmental monitoring tools, they can be described quantitatively and, thus, get an idea about the characteristics of the source of possible variations in the geomagnetic field (time, place, energy, light and acoustic manifestations, etc.). Despite the fact that observation and analysis of changes in the parameters of the geomagnetic field is a simple and effective method for studying the physical processes accompanying the fall of celestial bodies, nevertheless, the effect on the geomagnetic field of flights and the destruction of meteoroids has not been sufficiently studied. There are still various mechanisms for generating geomagnetic disturbances. Each of the proposed mechanisms may be responsible for the manifestation of certain disturbances in the geomagnetic field. Some of them can be distinguished: modulation of the system of ionospheric currents in the dynamo region of the ionosphere by disturbances coming from a meteor explosion [*Chernogor*, 2014; *Ivanov*, 1964, 2002], the formation of a dipole moment in the plasma trace [*Bronshten*, 2002], magnetic disturbance caused by a shock wave [*Bronshten*, 2002; *Ivanov*, 1964; *Siber et al.*, 2018], the appearance of a ballistic shock wave when a meteoroid enters more dense layers of the atmosphere [*Savchenko*, 1975], magnetohydrodynamic plume effect [*Catastrophic…*, 2005; *Chernogor*, 2018; *Kovalev et al.*, 2006], the appearance in the atmosphere of an additional magnetic moment formed by particles of a destroyed meteoroid [*Shaidurov*, 2015], the occurrence of various oscillations [*Chernogor*, 2011]. Another mechanism for the appearance of geomagnetic disturbances from the passage of a meteoroid may be its interaction with the Earth's plasmasphere [*Rakhmatulin et al.*, 2013]. Each of these mechanisms can make one or another contribution to the magnetic disturbance with its own spatio-temporal scales.

Let us consider the features of the behavior of geomagnetic field components and the possible reasons for their appearance. Figure 1 shows variations in the H, D and Z components of the geomagnetic field during a meteor explosion. The abscissa shows the time in UT, the vertical line shows the time of the meteor explosion. According to the all-sky camera data, the meteor flash was recorded at 19:03:07 UT. After approximately 110 s, a sharp change was noted in all components. At the same time, the nature of these measurements was different: in the H-component there is a sharp peak, in the D-component there is an N-shaped change, which in ionospheric studies is associated with the passage of a shock wave through the ionosphere, in the Z-component a W-shaped change is visible. The total change in the H-component was about 40 nT, in Z-component was about 60 nT, and in the D-component - about 80 nT.

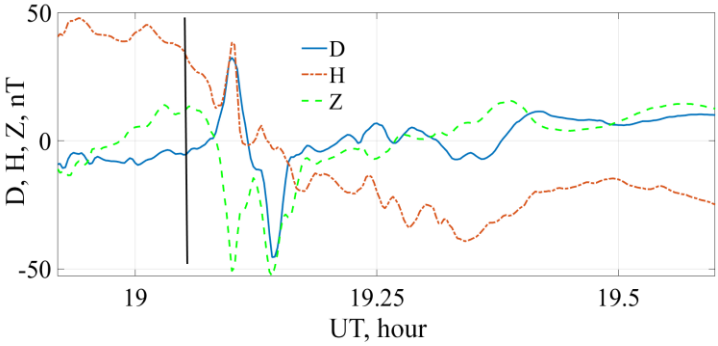

Figure 1. Variations of the geomagnetic field during a meteor explosion.

At the site of the explosion, an increased gas pressure is created by an order of magnitude and more superior to the pressure in the environment. Due to this, a shock wave appears with a significant initial amplitude, which propagates at a speed exceeding the speed of sound at ionospheric altitudes. As a rule, the shock wave weakens during propagation, generating acoustic, acoustic-gravity and slow magnetohydrodynamic waves.

Unlike middle and low latitudes, where meteoroid destruction processes are mainly considered, in high latitudes, meteor destruction occurs near a system of auroral electrojets. Let's consider the impact of the meteor explosion on this system. According to the MIRACLE monitoring system of the Finnish Meteorological Institute (The Magnetometers - Ionospheric Radars - Allsky Cameras Large Experiment) on the quicklook-plot of electrojets [*Miracle*, 2024; *Tanskanen*, 2009], during the meteor explosion, auroral electrojets were in the area of the Loparskaya Geophysical Observatory (Fig. 2). Therefore, as a first approximation for calculating the speed of propagation of the modulating effect from a meteor explosion on the current stream, you can choose the distance from the place of the meteor explosion to the height at which currents flow, creating variations in the geomagnetic field. According to estimates [*Zaitsev et al.*, 2022], it can be taken equal to 115 km. If we assume the height of the explosion to be 20 km, then the total distance from the explosion site to the current jet can be estimated at 95 km. In this case, the speed of propagation of the impact from the meteor explosion on the current jet with a reaction time of 110 s is approximately 860 m/s. Such velocities correspond to the propagation velocities of shock waves in the ionosphere. Note that after the meteor explosion, the quicklook graph clearly shows a sharp narrow change in the two eastern and western electrojets.

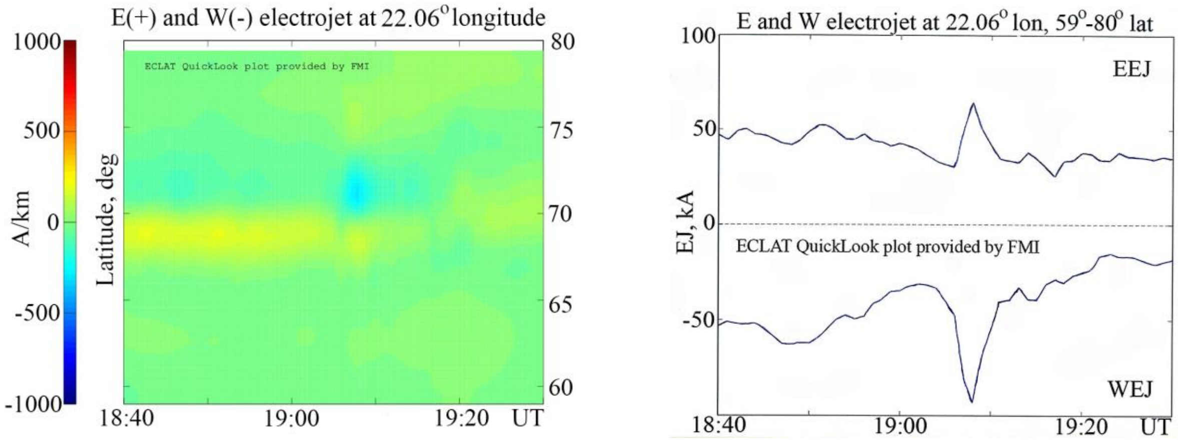

Figure 2. Behavior of equivalent eastern (E) and western (W) auroral electrojets at longitude 20.06°E (left) and the integral ionospheric equivalent current calculated separately for the eastern (EEJ) and western (WEJ) components (right) during the meteor explosion.

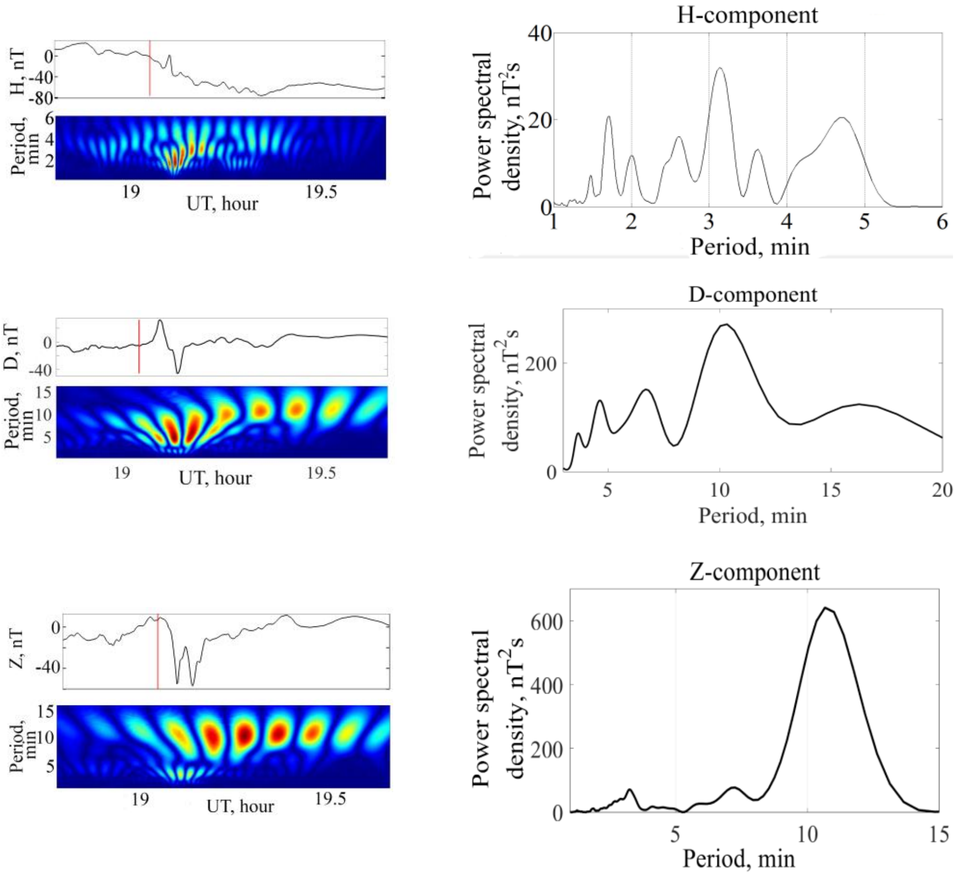

Figure 3. Variations in the geomagnetic field during the meteor explosion recorded at the Loparskaya Geophysical Observatory.

The clearly pronounced pulsed nature of the reaction of the geomagnetic field components at the Loparskaya Geophysical Observatory (Fig. 1) can be explained by the fact that this is a reaction to the impact of the shock wave from the meteor explosion on auroral electrojets. Thus, it can be argued that for the first time the impact of a shock wave from a meteor explosion on auroral electrojets has been discovered.

Let us consider variations in the components of the geomagnetic field recorded at the Loparskaya Geophysical Observatory during the meteor fall. Figure 3 shows the variations of components H (top picture), D (middle picture) and Z (bottom picture). The components are indicated along the ordinate axes. The abscissa shows the time in UT. In the figures, the vertical line shows the time of the meteor explosion.

The presence in the spectra of variations of period components that correspond to periods of acoustic-gravity waves in the E-region of the ionosphere speaks in favor of the hypothesis expressed in [*Chernogor*, 2014; *Ivanov*, 1964, 2002]. According to their assumptions, the wave-like change in the components of the geomagnetic field is explained by the fact that this is a reaction to the impact of acoustic-gravity waves on the system of ionospheric currents in the dynamo region of the ionosphere.

Conclusions. The behavior of the geomagnetic field after the meteor explosion over the Kola Peninsula is considered. The explosion is shown to have caused abrupt changes in the environment. The most likely mechanism for the manifestation of the changes in the geomagnetic field is the passage in the atmosphere of shock and acoustic-gravity waves generated during the explosion of the meteor. It was shown for the first time that a shock wave in the geomagnetic field had an impact on the auroral electrojets and caused sudden changes in their state. This in turn caused sharp changes in the components of the geomagnetic field. Subsequent wave-like changes are caused by the influence of acoustic-gravity waves on the system of ionospheric currents in the dynamo region of the ionosphere.

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