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Ionization Effects Caused by Precipitation of Energetic Electrons during Geomagnetic Disturbances

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Abstract—Energetic electron precipitation (EEP) into the Earth's atmosphere/ionosphere caused by various physical mechanisms and recorded by various instruments are studied separately. EEP events detected in balloon observations in the Murmansk region and from low-orbit Meteor-M2 satellite were used to estimate EEP effects on the atmosphere/ionosphere. Satellite energy channels from hundreds of keV to MeV were used to reconstruct the EEP energy spectra. To determine the atmospheric-ionospheric response to EEP during geomagnetic disturbances, calculated ionization rates were used based on spectra obtained from both satellites and balloon observations. The EEP spectra from satellites and balloon observations have practically the same slope, and only the particle flux intensity changes. The ionization rates throughout the altitude range on the last day of substorm activity are lower than during substorm activity maximum.

Keywords: energetic electron precipitation, EEP, satellite and balloon EEP observations, EEP induced ionization of atmosphere, ionosphere

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INTRODUCTION

Energetic electron precipitation (EEP) plays an important role contributing to the natural forcing of the polar ionosphere/atmosphere. Precipitating electrons collide with molecules of air and induce atmospheric ionization (formation of ion pairs), which affects many ionospheric and atmospheric processes and lead to variability of mesospheric and stratospheric ozone and the ionospheric electron density [1–4].

The most significant EEP from the outer electron radiation belt of the Earth occurs during geomagnetic storms. It is natural to assume that variations in the magnetospheric magnetic field should be one of the main factors controlling the dynamics of electron fluxes in the outer radiation belt of the Earth. Variations in the outer electron radiation belt can occur with the preservation of adiabatic invariants under the condition of relatively slow changes in the geomagnetic field compared to the characteristic times of electron movement. Just this situation can be observed during a geomagnetic storm. Periods of geomagnetic activity during which EEP was observed from low-orbit satellites and from balloons were determined.

Low-orbit satellites and balloon measurements enable recording fluxes of energetic particles precipitating from the outer radiation belt into the Earth's atmosphere/ionosphere [5–9]. Electron precipitation is most often observed during geomagnetic disturbances as a result of acceleration and scattering of captured particles followed by their entry into the loss cone. Since 1957, balloon measurements of ionizing radiation in the atmosphere have been regularly carried out at P.N. Lebedev Physical Institute, Russian Academy of Sciences [5]. Balloons measure fluxes of secondary cosmic rays, solar protons entering the atmosphere during energetic solar particle events, and bremsstrahlung of electrons as they precipitate from the outer radiation belt into the Earth's polar atmosphere. The energy spectrum of precipitating electrons is retrieved from observations of the absorption of bremsstrahlung X-rays in the atmosphere. A technique for converting X-ray fluxes in the atmosphere to the energy spectrum of electrons was developed based on Monte Carlo calculations [10]. The fluxes of precipitating electrons often strongly fluctuate over time. Therefore, only the cases of monotonic increase in X-ray fluxes during balloon ascent are selected for correct retrieval of the spectrum.

Polar orbit satellites, such as Meteor-M2, perform measurements which allow EEP to be identified by the ratio of electron fluxes measured by vertical and horizontal detectors. Data from Meteor-M2 detectors (100 keV, 700 keV, and 2 MeV channels), which

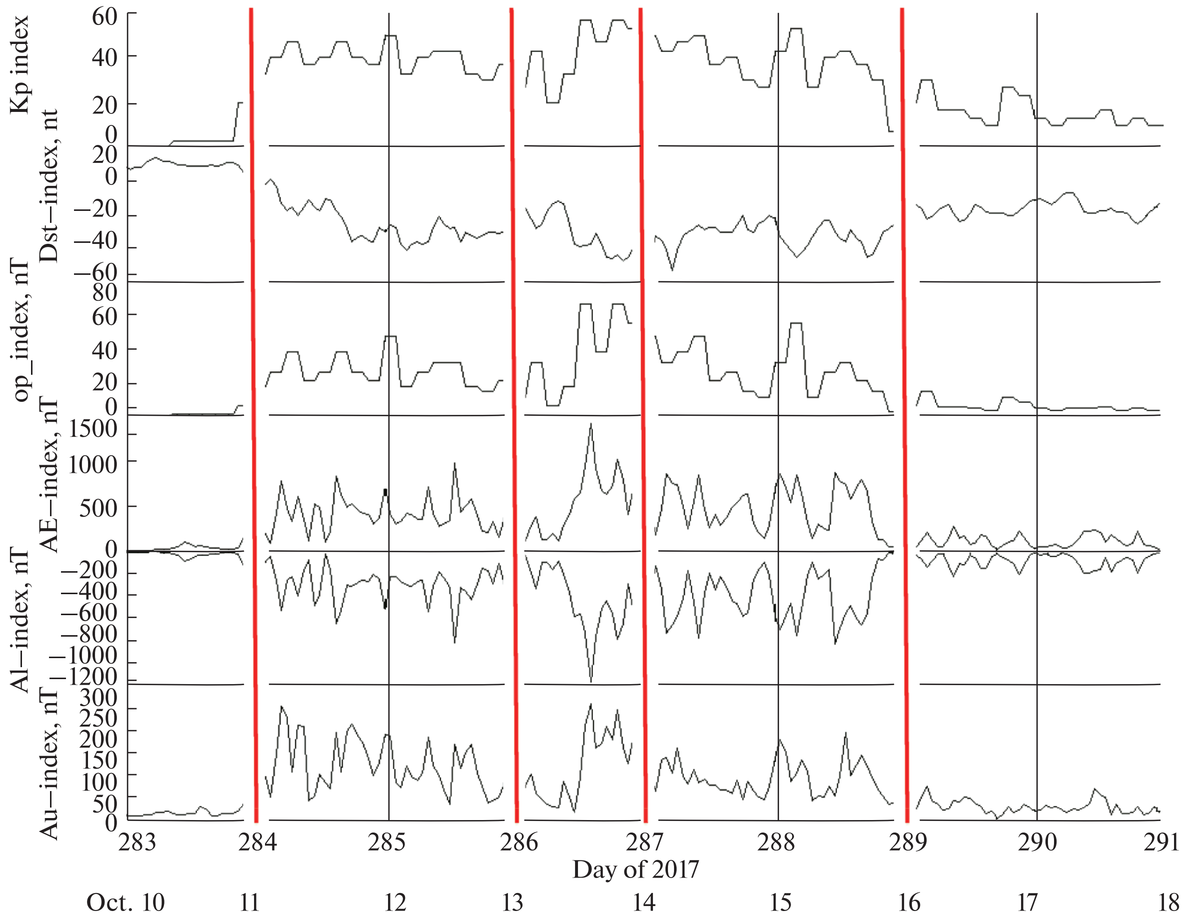

Fig. 1 Variability of geomagnetic indices in October 2017 (https://omniweb.gsfc.nasa.gov/form/dx1.html). Red lines show days when EEP was detected by Meteor-M2.

showed the dynamics of fluxes at altitudes of about 800 km, were used to estimate the EEP fluxes at satellite altitudes.

The aim of the work is to compare the spectra obtained during EEP from the satellite and balloons and calculate the ionization rates during different phases of the substorm based on these spectra.

1. GEOMAGNETIC STORM UNDER STUDY

We have selected several EEP events for which the widest possible sets of magnetospheric measurements of the magnetic field, energetic particle fluxes, etc. are available A magnetic storm accompanied by prolonged substorm activity was observed on October 10–16, 2017. The choice of the period was due to the availability of data from Meteor-M2 low-orbit satellites and measurement data from Lebedev Physical Institute balloons [5] launched from the Lovozero station (MLT = UT + 2.6) of the Murmansk region (geomagnetic latitude of about 64° N) at that time.

Data from simultaneous measurements of solar wind by spacecraft, magnetospheric satellites, and ground stations were used to study variations in the Earth's outer radiation belt during October 10–16, 2017. In that period, extensive coronal holes were observed on the Sun, and high-speed solar wind flows entered the Earth's orbit, causing moderate geomagnetic disturbances with maximal amplitude of about 50 nT. Long-term substorms were observed at high latitudes, and sharp changes in relativistic electron fluxes occurred in the geostationary orbit. It is evident that the increase in substorm activity began on October 11, 2017, and continued for several days. Around midday of October 13, an additional increase in substorm activity was observed, simultaneously with a continuing increase in the solar wind speed and a repeated increase in the *Dst* amplitude (Fig. 1).

The geomagnetic disturbance began at the end of October 10 and ended at the end of October 16, 2017. That five-day storm began with an increase in the solar wind speed from 400 to 700 km/s by the middle of the interval. Intense auroral activity was confirmed by an

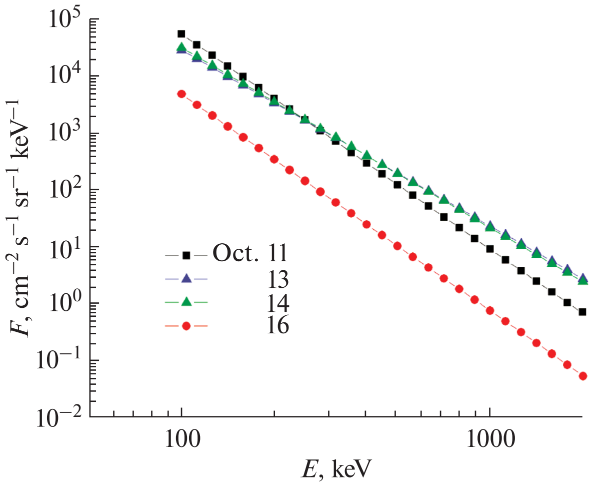

Fig. 2. EEP Spectra retrieved from Meteor-M2 observations in October 11–16, 2017.

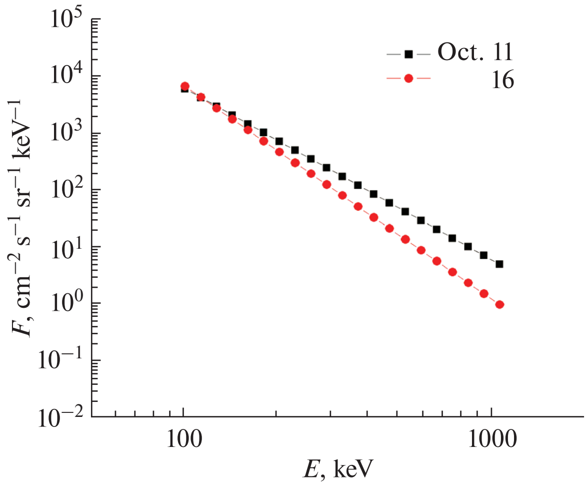

Fig. 3. EEP Spectra retrieved from balloon observations on October 11 and 16, 2017.

increase in the *AE* index to 1500 nT. At the same time, the magnetic storm was weak, the *Dst* index did not exceed −60 nT. Substorm activity reached its maximum around October 13, 2017 (see Fig. 1).

2. METEOR-M2 AND BALLOON OBSERVATIONS AND SPECTRA

Meteor-M2 is equipped with multidirectional detectors for measuring electron fluxes above 100 keV, with the ability of measuring relativistic electron fluxes above 2 MeV. The ratio of the fluxes of the detectors directed along the spacecraft orbit and at the zenith allows determining the time and location of EEP. In 2017, Meteor-M2 spacecraft had a sun-synchronous orbit, which was located in 10–13 MLT and 21–00 MLT sectors. During October 10–16, 2017, Meteor-M2 measured EEP from 18 UT to 24 UT in the geographic latitude range from 60° to 70° S.

Precipitating electrons in the energy range from tens of keV to more than 1 MeV generate bremsstrahlung. These electrons are absorbed at altitudes above than 50 km, but the generated bremsstrahlung X-rays penetrate into the atmosphere down to altitudes of about 30 km and can be detected by a balloon Geiger counter [5]. Balloon observations were performed over the Murmansk region (68 N) at about 13 UT, 15 MLT, on October 11 and at about 13 UT, 15 MLT, on October 16.

Figures 2 and 3 show examples of EEP spectra obtained from the Meteor-M2 satellite and balloon observations during the geomagnetic disturbance in October 2017. Though some EEP were recorded at an altitude of about 30 km and others at about 800 km, the EEP spectra have practically the same slope, and only the particle flux intensity differs. To retrieve the ionization rate of the atmosphere (formation of ion pairs per second), it is necessary to have information on the energy spectra (particle energy and flux intensity) and the parameterization of ion formation from the point of view of the atmospheric response function [11]. The atmospheric response function to EEP at a certain atmospheric depth is the number of ion pairs created by one precipitating electron with an initial energy at the top of the atmosphere. In this work, we use modified functions for monoenergetic electrons and take into account both direct ionization by primary electrons and secondary bremsstrahlung [11].

3. IONIZATION OF ATMOSPHERE AND IONOSPHERE

EEP into ionosphere/atmosphere induces ionization of the atmosphere. The ionization rates of the atmosphere are the key parameter for estimation ozone destruction and climate change under energetic particle forcing. The atmosphere/ionosphere ionization rates calculated for the period under study taking into account the atmospheric response function [11] and energetic electron precipitation spectra recorded in October 2017 during balloon and Meteor-M2 observations (see Figs. 2 and 3) are shown in Figs. 4 and 5, respectively. Despite the differences in the slope of the spectra and the intensity of energetic electron fluxes in October 11–16, 2017, the rates of atmosphere/ionosphere ionization due to EEP retrieved from satellite and balloons spectra similarly behave throughout the altitude range from 20 to 120 km and change by 12 orders of magnitude with altitude.

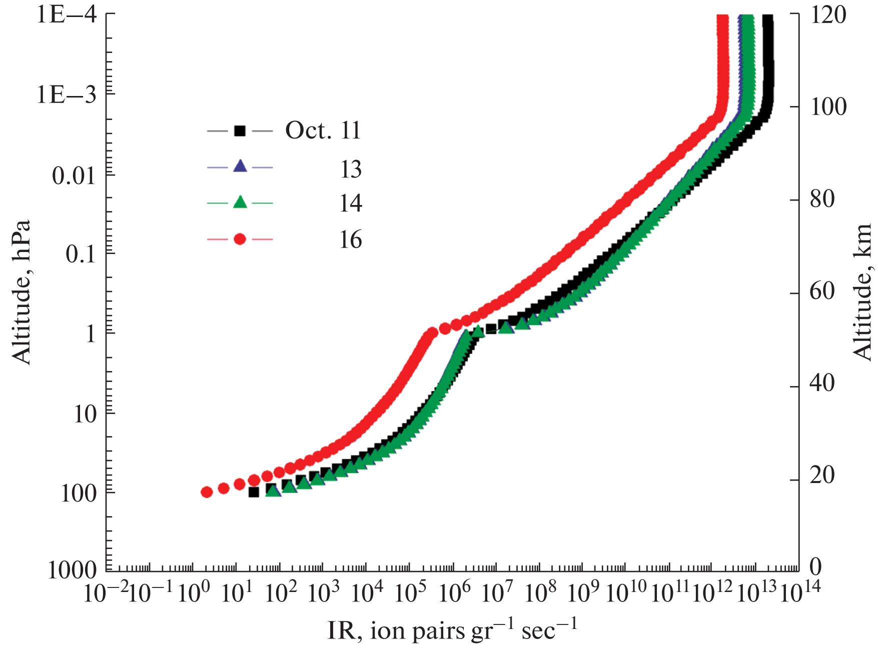

Fig. 4. Atmosphere/ionosphere ionization rates calculated from EEP spectra retrieved from Meteor-M2 observations in October 11–16, 2017.

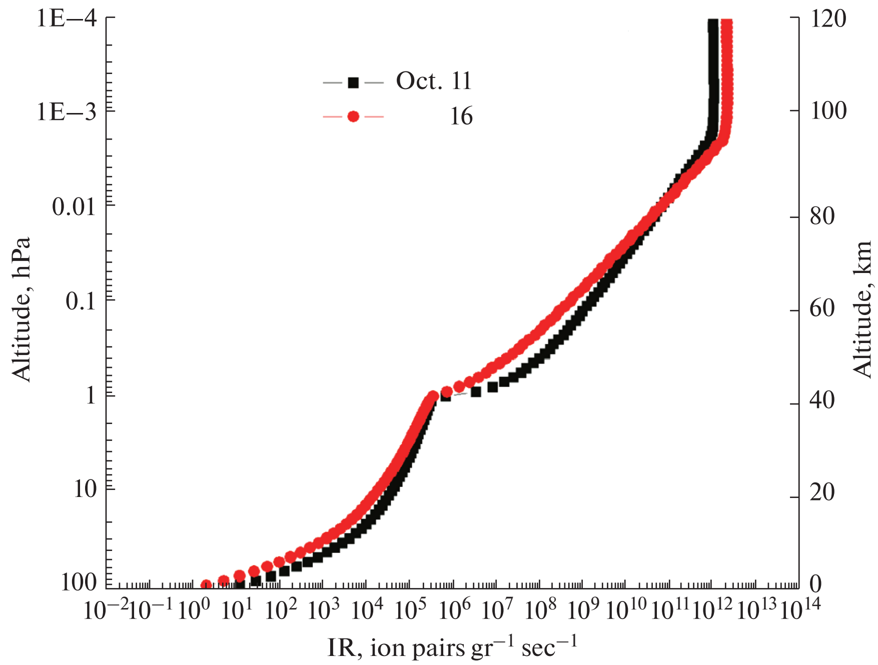

Fig. 5. Atmosphere/ionosphere ionization rates calculated from EEP spectra retrieved from balloon observations on October 11 and 16, 2017.

CONCLUSIONS

Energetic electron precipitation during a magnetic storm on October 10–16, 2017, accompanied by long-term substorm activity was investigated from ionospheric/atmospheric point of view. The rates of EEP induced ionization are computed based on the spectra obtained from the Meteor-M2 low-orbit satellite and balloon measurements. Though EEP was detected at an altitude of about 30 km by balloons and at about 800 km by the satellite, the EEP spectra have practically the same slope, and only the particle flux intensity differs. Ionization rates throughout the altitude range from 20 to 120 km are lower on the last day of substorm activity than during substorm activity maximum.

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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