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Large Amplitude Undulations of Evening Site Diffuse Aurorae. Optical Characteristics and Conditions of Generation

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Abstract—Optical characteristics of large amplitude undulations (LAU) of diffuse aurorae observed by all-sky cameras at Kola Peninsula on December 28, 2010 were examined. Both interplanetary medium conditions and characteristics of magnetic activity before and during LAU were analyzed. It was shown that the development of undulations could be activated by sharp short-living of ~20 minutes solar wind dynamic pressure impulse and existence of the undulations during about two hours was supported by electric field of stationary magnetospheric convection originated from large smoothly changed southward IMF *Bz* component of about −12nT. The altitude of undulation luminosity determined by triangulation method was 120 ± 10 km. The undulations amplitude changed from about 100 to 300 km and the average wavelength was ~250 km. The undulations were observed moving westward with the average phase velocity of ~0.7 km/s. The pass of DMSP F16 spacecraft just along "the tongue" of undulations showed that the wave of luminosity was located in the region of the predominantly ion (proton) precipitation with the average energy of particles of ~18 keV. Rayed auroral structures were observed continuously in the region of diffuse aurorae during time interval of LAU existence. These structures were observed moving westward with the velocity of about 2 km/s that corresponds to the northward electric field of ~100 mV/m.

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1. INTRODUCTION

Large-scale undulations (LAUs) at the equatorward edge of diffuse auroras were for the first time presented in (Lui et al., 1982). Using the auroral images from the DMSP satellites, these authors detected four LAU events and presented their generalized characteristics. All luminosity undulations were registered in the evening sector during magnetic storms near the peak *Dst* values. Luminosity undulations existed during 0.5–3.5 h, the undulation amplitude varied from 40 to 400 km, and the wavelength varied from 200 to 900 km. The DMSP static images did not allow the authors to determine the LAU dynamic characteristics. Such studies were performed later based on the all-sky camera observations. The first data indicating that LAUs move westward were presented in (Nishitani et al., 1994). The authors analyzed one event that lasted slightly more than 20 min and managed to detect four complete luminosity undulations. The undulation amplitude varied from 70 to 140 km, the average wavelength was ~140 km, and the phase velocity was 0.5–0.7 km/s. When these calculations were performed, the auroral altitude was taken as equal to 100 km.

Using the all-sky camera data from Eastern Siberia, Baishev et al. (2000) studied a LAU event that lasted ~80 min and had an undulation amplitude varying from 50 to 250 km and a wavelength of 200–300 km. Luminosity tongue propagated westward at a velocity of ~0.7 km/s under the assumption that their altitude was 110 km. Henderson et al. (2010) published the studies of larger-scale luminosity undulations that existed for approximately 2 h during the magnetic storm that occurred on November 24, 2001. The velocity of luminosity undulations with an amplitude about 900 km and a wavelength of ~700 km was ~0.9 km/s relative to the Earth's surface. To determine the LAU characteristics based on ground data, it is necessary to know the luminosity altitude. Proceeding from the general concepts of the auroral emission altitude, different authors accepted that the luminosity undulation altitude is 100–110 km, although this altitude has not yet been specially studied by the triangulation and any other methods.

In (Lui et al., 1982) and other studies cited above, it was noted that bright auroras and westward travelling surges—forms typical of the substorm development—were observed at the diffuse luminosity poleward edge during LAUs. It is insufficiently clear whether substorm activity substantially affects the generation of luminosity undulations. Thus, Baishev et al. (2010) considered the LAU event on December 12, 2004, when the ground based all-sky camera registered eight luminosity undulations with a 100–150 km amplitude and a wavelength of 200–300 km at Tiksi observatory. This event lasted ~1 h during a relatively quiet period between two substorms in the magnetic field. Nevertheless, bright discrete auroras and auroral surges were also registered on DMSP satellites in the poleward part of luminosity band during this event. Such auroral forms apparently exist in the evening sector, because this interval corresponded to the magnetic storm recovery phase.

The mechanism by which LAUs are generated has not yet been completely determined; however, the researchers assume that the considerable convection velocity gradients substantially affect the generation of such waves at subauroral latitudes. The presence of increased convection streams at latitudes below the auroral oval was referred to for the first time in (Galperin et al., 1974), where these streams were called "a polarization jet". These phenomena were subsequently more generally called "subauroral polarization streams" (SAPS) (Foster and Burke, 2002). Goldstein et al. (2005) presented the SAPS magnetospheric model and indicated that the waves can originate at the plasmapause as a result of substorm injections. Mishin and Mishin (2007) indicated that polarization streams sharply intensify approximately 10 min after substorm onset during magnetic storms. This intensification starts when the westward-traveling surge (WTS) reaches the adjacent auroral region in the evening sector.

The appearance of LAUs can be considered a rather rare phenomenon. This follows at least from the fact that DMSP images are available from 1972, and the first publication on this phenomenon appeared only in 1982 (Lui et al., 1982). Only four LAU events were detected during this 10-year period of studies. All of the subsequent publications are mainly concentrated on studying isolated events or several events in exceptional circumstances.

The present work studied in detail the LAUs that were registered at the observatories on the Kola Peninsula on December 28, 2010. The aim of this work is to study in detail the optical characteristics of undulations and to determine the conditions in the interplanetary medium and the Earth's magnetosphere that accompanied the generation of these undulations. We showed that luminosity undulations could be initiated by the solar wind dynamic pressure impulse, and their existence for approximately 2 h was supported by the electric field of stationary magnetospheric convection.

2. LAUs AND THEIR GENERATION CONDITIONS

The LAUs studied in this work were registered with the all-sky cameras on the Kola Peninsula at 1400–1600 UT on December 28, 2010. Figure 1a shows the aurora keogram along the geomagnetic meridian, obtained at Lovozero observatory (LOZ, $\Phi' = 64.17°$, MLT = UT + 2.6). The keogram was constructed in the region of zenith angles ±80°, and the universal time is plotted on the abscissa. Figure 1a indicates that LAUs were observed in the early evening hours (~1640–1840 MLT) at the equatorward edge of diffuse auroras, whereas bright discrete auroras were located at the poleward edge of luminosity. Figure 1b illustrates at the poleward edge of luminosity these luminosity undulations in corrected geomagnetic latitude–UT coordinates (CGL–UT).

The solar wind and IMF parameters, as well as the magnetic activity characteristics, were analyzed based on 1-min OMNI data (http://cdaweb.gsfc.nasa.gov), some of which are presented in Fig. 2 in a widened interval (from 1000 to 1800 UT). The interval of LAUs observation is marked by vertical lines. Figure 2 indicates that luminosity undulations appeared after a sudden short-living (~20 min) impulse of solar wind dynamic pressure, which was accompanied by an almost synchronous increase in magnetic activity in the auroral zone (the *AL* index) and by an increase in *SYM/H* related to the compression of the dayside magnetosphere. The pressure impulse was caused by only a plasma density jump from approximately 14 to 56 cm^{-3}, immediately after which (~1400–1600 UT) the interplanetary medium parameters changed insignificantly: the IMF *Bz* and *By* values were approximately –12 and +7 nT, respectively; the dynamic pressure was ~4 nP. Although certain activity variations were observed in the *AL* index during that period, the average activity values remained about –700 nT. Such characteristics of IMF, solar wind plasma, and magnetic activity may indicate that stationary magnetospheric convection (SMC) existed at 1400–1600 UT. The existence of prolonged periods with SMC, which develop under the action of a prolonged quasistationary southward IMF, was shown for the first time in (Sergeev, 1977; Pitte et al., 1978). Pronounced *Dst* disturbances, fluctuating disturbances at auroral latitudes, and the two-vortex current system in the polar region are observed during the periods with SMC. On the other hand, analysis of the satellite observations indicates that substorm signatures are absent over several hours of high geomagnetic activity, which indicates that the magnetosphere and ionosphere are quasistationary (Sergeev, 1977; Pitte et al., 1978).

Figure 3 shows the longitudinal variations in the amplitude of the geomagnetic field *H* component at the chain of high-latitude stations at 14–15 UT (a solid line) and 15–16 UT (a dashed line) on December 28, 2010. The stations used in the work are listed in table. The magnetic field value on a magnetically quiet day (December 27, 2010) was taken as a zero level. To construct the longitudinal variations, we took the maximal deviation of the magnetic field *H* component at each station from the quiet level in the corresponding UT interval. Note that the longitudinal distributions presented in Fig. 3 are similar to one another, which indicates that the ionospheric currents are distributed relatively stable and correspond to the two-vortex current system with maximums about 16 and

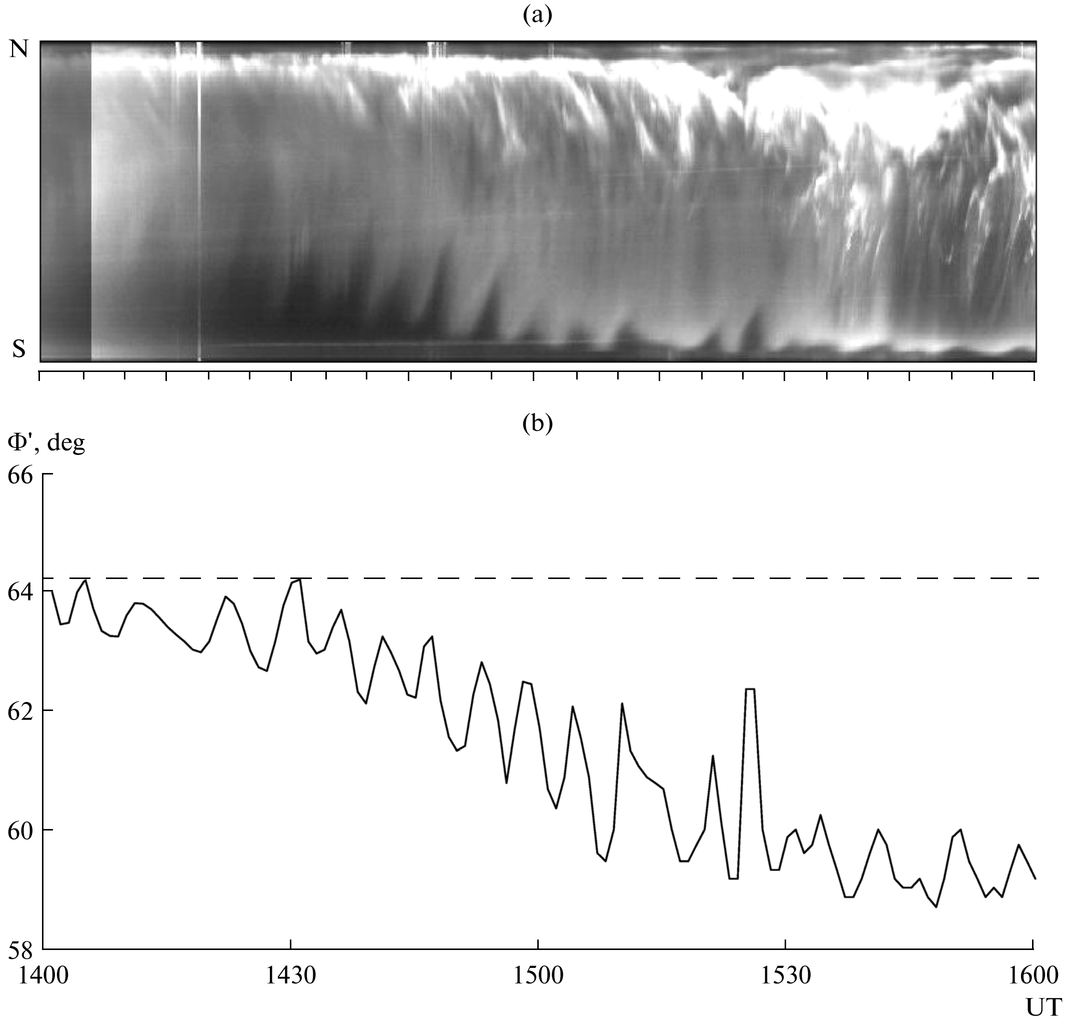

Fig. 1. (a) Keogram of auroras at 1400–1600 UT performed in the geomagnetic meridian direction. (b) The position of the diffuse luminosity equatorward boundary in corrected geomagnetic latitude–UT coordinates.

04 MLT. Such a current system is the intense current system of the DP2 type rather than the DP1 substorm current system. Thus, using the ground-based and satellite observations, Elpinstone et al. (1995) indicated that substorms start at latitudes of 63.8° ± 3.3° MLAT in the 22.9 ± 1.1 MLT sector. Correspondingly, the maximal level of magnetic disturbances during substorms would also be anticipated in the premidnight sector.

The characteristics of auroras during the periods with SMC were studied for several events in (Sergeev and Vorobjev, 1979) and then in (Yahnin et al., 1994) during the period with SMC that was continuously observed for more than 10 h. Both groups of researchers presented schemes describing the large-scale distribution of auroras during SMC periods. A clearly defined diffuse luminosity band with bright discrete auroras in its poleward zone is the characteristic feature of such a distribution in the evening–midnight sector. In the evening sector, bright auroras look like a surge that does not propagate westward, however, as would be observed during substorms, and is located in approximately the same MLT sector during the entire SMC period, indicating that the magnetospheric structure is relatively stationary.

Figure 4c presents the DMSP F16 auroral image during the period when LAUs were registered with all-sky cameras. The Kola Peninsula is approximately at the image center in the diffuse luminosity region, the equatorward edge of which is undulating. Such a location of diffuse and discrete auroras is similar to the distribution observed during SMC periods. Figures 4a and 4b indicate that the diffuse luminosity band in the evening sector also existed before the LAU period before the solar wind dynamic pressure impulse (Fig. 4a) and during the period of activity related to the impulse (Fig. 4b). However, LAUs were not observed in both cases. It is difficult to judge the dynamics of discrete auroras using three DMSP images taken at a certain time interval. However, since the DMSP orbits are ori-

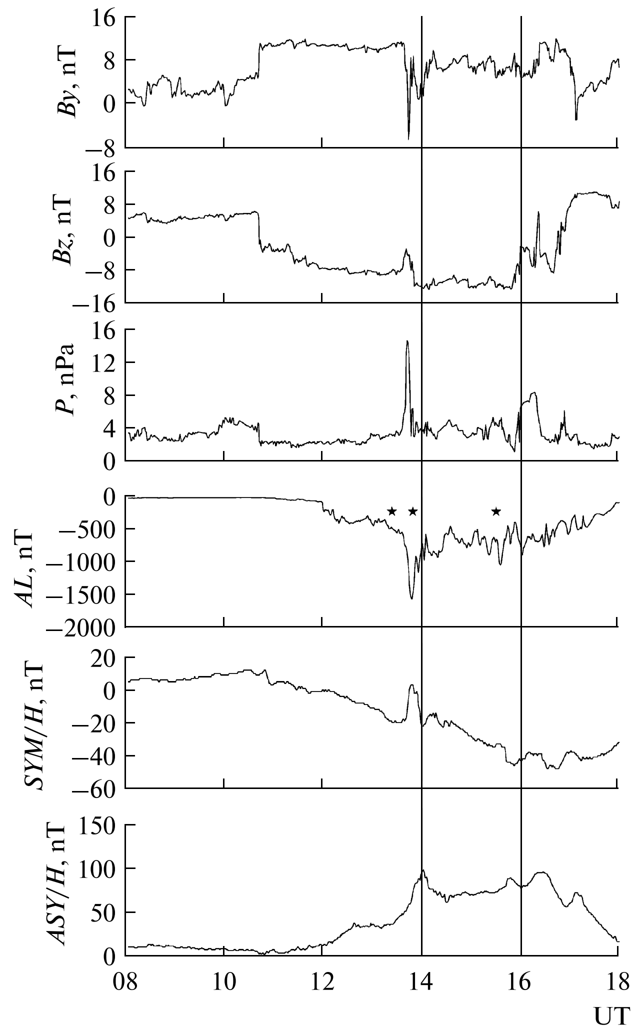

Fig. 2. Interplanetary medium parameters and geomagnetic activity characteristics on December 28, 2010, at 1000–1800 UT. From top to bottom: the IMF *By* and *Bz* components; solar wind dynamic pressure (*P*); and *AL*, *SYM*/*H*, and *ASY*/*H* geomagnetic activity indices. The LAU observation period is marked by vertical lines. The DMSP satellite pass time is shown by asterisks on the *AL* index panel.

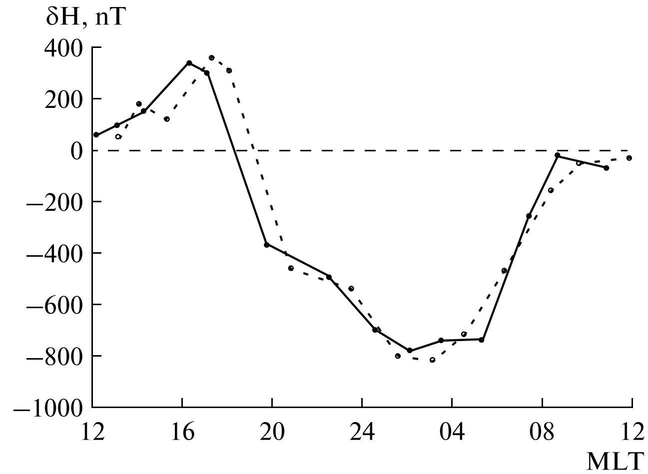

Fig. 3. Variation in the magnetic field *H* component at the longitudinal chain of stations at 14–15 UT (solid line) and 15–16 UT (dashed line) on December 28, 2010.

ented with respect to the Sun, all images in Fig. 4 cover an approximately identical MLT interval in the auroral region. A comparison of the images shows that the bright surges in discrete auroras were located in the approximately the same MLT sector, which can indicate that the spatial distribution of auroras was relatively stable over a prolonged period.

Considering Fig. 2 again, we can note that geomagnetic disturbances started at approximately 1040 UT as a result of the interaction between the Earth's magnetosphere and the solar wind inhomogeneity, which had a sharp leading front. This instant can be considered as the beginning of a small magnetic storm with the *Dst* maximum (about –50 nT) at 16–17 UT. Within the solar wind inhomogeneity before the dynamic pressure impulse, the IMF and plasma parameters varied insignificantly, and negative values of the IMF *Bz* component smoothly increased. The longitudinal variations in the amplitude of the geomagnetic field *H* component immediately before the solar wind dynamic pressure impulse (1230–1330 UT) and during the impulse (1330–1400 UT) looked as in Fig. 3 for the LAU period but had larger and smaller amplitudes, respectively.

The ground-based and satellite observations illustrated above make it possible to interpret the entire considered interval as a period of two-step SMC. At rather uniform conditions in the interplanetary medium, the SMC was formed immediately after ~12 UT with the magnetic disturbance in the morning sector about –400 nT. This SMC period was terminated by the solar wind dynamic pressure impulse, which was accompanied by an abrupt short-living increase in magnetic activity at ~1330–1400 UT. After ~14 UT, stationary convection recovers again but with the magnetic disturbance in the morning sector about –700 nT. This SMC period continued up to ~1630–1700 UT, after which the magnetic disturbance decreased to the quiet level, which was accompanied by an increase in the IMF vertical component. The asymmetric part of the ring current (the *ASY*/*H* index in Fig. 2) shows the same two steps.

3. LAU OPTICAL CHARACTERISTICS

Some characteristics of LAUs can be extracted from Fig. 1. Figure 1b illustrates luminosity undulations in CGL–UT coordinates. When the LAU latitude was determined, the luminosity altitude was taken as equal to 120 km. The luminosity altitude was determined by the triangulation method using all-sky camera observations at Apatity and Lovozero observatories with geographic coordinates φ = 67.58° N, λ = 33.31° E and φ = 67.97° N, λ = 35.02° E, respectively. To determine the auroral altitude, more exact camera positions were determined using GPS. Since the luminosity undulation boundary is rather indistinct, the areas with the most distinct luminosity boundary at different angles of sight and UT instants on camera images were selected in Apatity. The position of each point selected at the luminosity boundary in Apatity was subsequently determined on a simultaneous image in Lovozero with variation of the luminosity altitude from 100 to 140 km at an interval of 5 km. The altitude of the closest coincidence of the boundaries was registered in both cases. The series of such calculations gave an LAU altitude equal to 120 ± 10 km, which corresponds to the height of ion production rate maximum for electrons with energies from 2 to 6 keV and/or protons with energies from 10 to 30 keV (Isaev and Pudovkin, 1972).

The equatorward boundary of luminosity undulations shifted toward the equator during the observations, which was accompanied by a simultaneous increase in the negative *SYM*/*H* values. Nineteen peak values of the diffuse luminosity equatorward boundary position were registered during 2 h of the LAU existence. The undulation amplitude varied from ~100 to 300 km and distinctly tended to increase toward the interval center and to decrease toward the end of the interval. At the Lovozero meridian, the average period of variations in the boundary was ~6 min, which corresponds to the period of *Pc*5 geomagnetic pulsations.

The all-sky camera images from Lovozero observatory (see Fig. 5) illustrate the shape of variations in the diffuse luminosity equatorward boundary. The black–white camera registered the airglow at an interval of 1 s; however, the images are presented at an interval of 30 s (a) at 1444:30 UT, (b) at 1445:00 UT, (c) at 1445:30 UT, and (d) at 1446:00 UT in order to show the luminosity undulation westward motion. The camera orientation in geomagnetic coordinates is shown in the lower right corner of the figure: the northward and eastward directions are shown at the top and on the right, respectively. The diffuse luminosity equatorward boundary is marked by a thin dashed line in order to increase the contrast.

The diffuse luminosity boundary position in the geographic coordinate system is illustrated in Fig. 6,

The longitudinal chain of magnetic stations

No.	Station	Φ'	MLT = UT+
1	Tromso	66.7	+1.8
2	Lovozero	64.2	+2.6
3	Dikson	68.3	+5.3
4	Tiksi	65.4	+8.0
5	Pevek	65.8	+10.1
6	Kiana	65.0	+11.6
7	Inuvik	75.1	+13.0
8	Yellowknioft	70.0	+14.8
9	Fort Churchill	69.6	+16.9
10	Kapuskasing	60.9	+18.2
11	Kuujjuaq	65.1	+20.4
12	Kangerlussuaq	73.9	+21.7
13	Tasiilag	70.0	+22.6
14	Ittoqqortooniit	72.1	+23.8

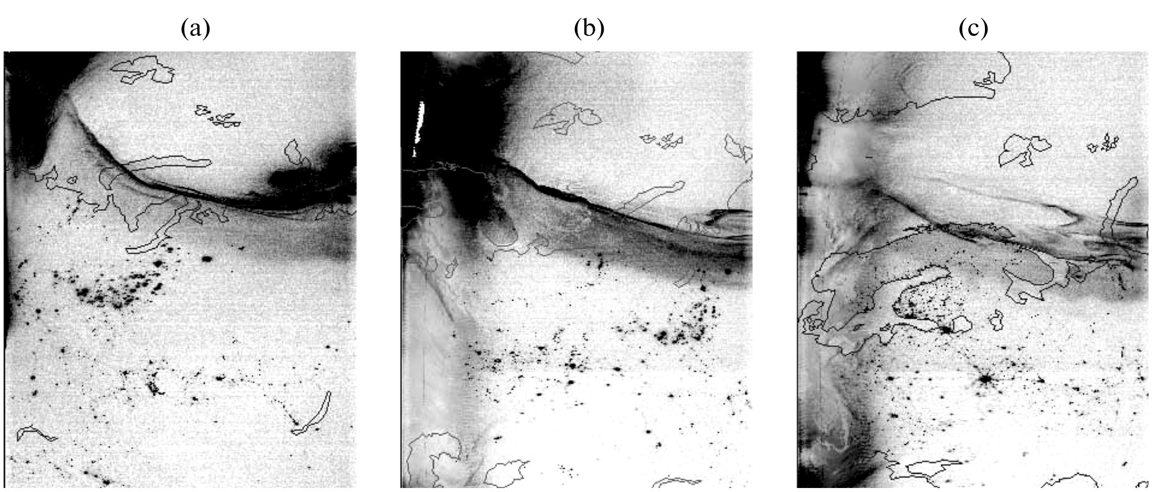

Fig. 4. Auroras registered on December 28, 2010, (a) by DMSP F18 at 1323 UT and by DMSP F16 at (b) 1347 UT and (c) 1529 UT.

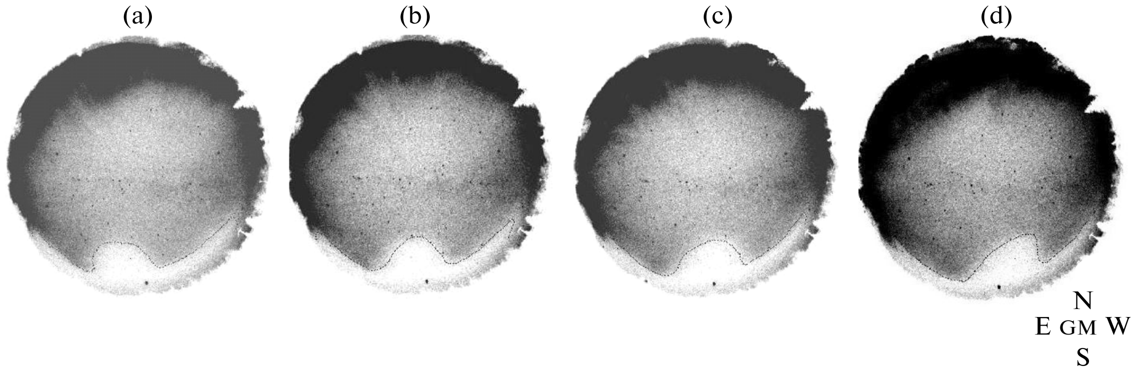

Fig. 5. All-sky camera photographs taken at Lovozero observatory at (a) 1444:30 UT, (b) 1445:00 UT, (c) 1445:30 UT, and (d) 1446:00 UT. The camera orientation in geomagnetic coordinates is shown in the lower right corner. The diffuse luminosity equatorward boundary is marked by a dashed line in order to increase the contrast.

which shows luminosity waves at an interval of 1 min: (a) 1445:00 UT, (b) 1446:00 UT, (c) 1447:00 UT, (d) 1448:00 UT, and (e) 1449:00 UT. The approximate centers of two adjacent luminosity bays are joined by vertical dashed lines in Fig. 6, which makes it possible to estimate the wavelength and undulation westward velocity. The distance between dashed lines (the wavelength) is ~7° of longitude, which corresponds to ~280 km at 67° latitude, and the luminosity bay phase velocity is ~5 deg min^{-1} or ~0.7 km/s. If we assume that this velocity approximately corresponds to the average phase velocity, we find that the average wavelength is ~250 km assuming the average period of undulations at the Lovozero meridian of 6 min. Wave crests are inclined to the opposite of the motion direction, which can mean that the convection velocity in the wave bay is higher than at the wave crest. Such configuration of undulations were previously mentioned by (Lui et al., 1982; Nishitani et al., 1994).

Figure 7 shows the configuration of the diffuse luminosity equatorward boundary and the DMSP F16 trajectory leg in the geographic coordinate system. The satellite direction is shown by an arrow. The dots on the trajectory show the satellite position at 1528:00 and 1529:00 UT. The diffuse luminosity boundary was constructed using the all-sky camera data at Lovozero observatory at 1528:20 UT, when the satellite was near this boundary. Figure 7 indicates that the satellite trajectory passes precisely along the luminosity "tongue." The position of the equatorward boundary of ion (*1*) and electron (*2*) precipitation is shown by numerals *1* and *2* on the trajectory, respectively. Thus, leg *1*–*2*, which is in close agreement with the luminosity "tongue" boundaries, corresponds to the spatial region where only ion (mostly proton) precipitation with an average ion energy of ~18 keV is registered. At higher latitudes, the F16 satellite registered both ion and electron precipitation in the diffuse luminosity region, whereas the bright discrete auroras at the poleward oval edge are related to only electron precipitation with an energy reaching several kiloelectronvolt. The spatial distribution of auroras obtained by the F16 satellite during this pass was shown in Fig. 4c, where the satellite trajectory passes from bottom to top at the frame center.

The auroral luminosity keogram (Fig. 1a) and individual frames of the all-sky camera (Fig. 5) show that bright discrete auroras are present in the diffuse luminosity poleward zone. However, sometimes very intense rayed structures, oriented at different azimuthal angles often in a direction close to N–S, were also continuously observed in the diffuse luminosity region. Such structures rapidly moved westward. Successive frames of the all-sky camera and the inclination of the aurora motion lines on the keograms performed in the E–W direction made it possible to calculate the aurora velocities presented in the 1400–1800 UT interval in Fig. 8. The average velocities in each half-hour interval are shown by solid lines. Figure 8 indicates that the average aurora velocity was considerable (~2 km/s) when LAUs were registered, from 1400 to 1600 UT. Such a velocity is approximately three times as high as the luminosity undulation velocity at the equatorward edge of diffuse auroras and corresponds to a northward electric field of ~100 mV m^{-1}. The frequently observed clockwise rotation of rayed structures, which resulted in a considerable scatter of dots in Fig. 8 at 1400–1600 UT, may indicate that the equatorward electric field gradient is present in the diffuse luminosity region.

A rapid decrease in the aurora velocity, observed in Fig. 8 after ~1600 UT, was accompanied by a damping and complete disappearance of fluctuations at the diffuse luminosity equatorward edge. Although luminosity undulations evidently moved outside the convection field, such synchronism can indicate that a certain relationship exists between the electric field within the diffusion region and the undulation generation at the equatorward boundary of this region.

A decrease in the convection electric field after 1600 UT is in turn related to the beginning of an increase in the IMF *Bz* component, which is accompanied by a corresponding decrease in the intensity of the two-vortex ionospheric current system. The latter can be observed in Fig. 2 by a gradual decrease in activity in the auroral zone (the *AL* index).

4. RESULTS AND DISCUSSION

We studied in detail the optical characteristics of LAUs, which were observed with the all-sky cameras on the Kola Peninsula on December 28, 2010. We analyzed the conditions in the interplanetary medium and the geomagnetic activity characteristics before LAUs and during the period when they were registered. We indicated that the luminosity undulation generation could be initiated by a short-living (~20 min) sudden impulse of the solar wind dynamic pressure. Luminosity undulations were observed for 2 h in the interval from ~1400 to 1600 UT, which can be characterized as a period of SMC that formed under the action of a large (about −12 nT) and weakly varying negative IMF *Bz* component.

Luminosity undulations were registered in the evening sector (~1640–1840 MLT) at the equatorward edge of diffuse auroras. An analysis of the optical observations made it possible to determine the following undulation characteristics:

1. The luminosity undulation altitude, determined using the triangulation method, was 120 ± 10 km.

2. The undulation amplitude varied from ~100 to 300 km and distinctly tended to increase toward the LAU observation interval center and to decrease at the end of this interval. The average wavelength was ~250 km. Luminosity undulations moved westward at an average phase velocity of ~0.7 km/s.

3. The F16 satellite pass along the luminosity "tongue" indicated that the luminosity undulation was in the region of only ion (proton) precipitation, the average energy of which was ~18 keV.

4. Rayed structures, oriented at different azimuth angles often in a direction close to N–S, were continuously observed in the diffuse luminosity region. The frequently observed clockwise rotation of such structures may indicate that the equatorward electric field gradient exists in the diffuse luminosity region.

5. When LAUs were registered, such rayed structures moved westward at an average velocity of ~2 km/s, which corresponds to a northward electric field of ~100 mV m^{-1}. A rapid decrease in the rayed aurora velocity was accompanied by a damping and complete disappearance of fluctuations at the diffuse luminosity equatorward edge.

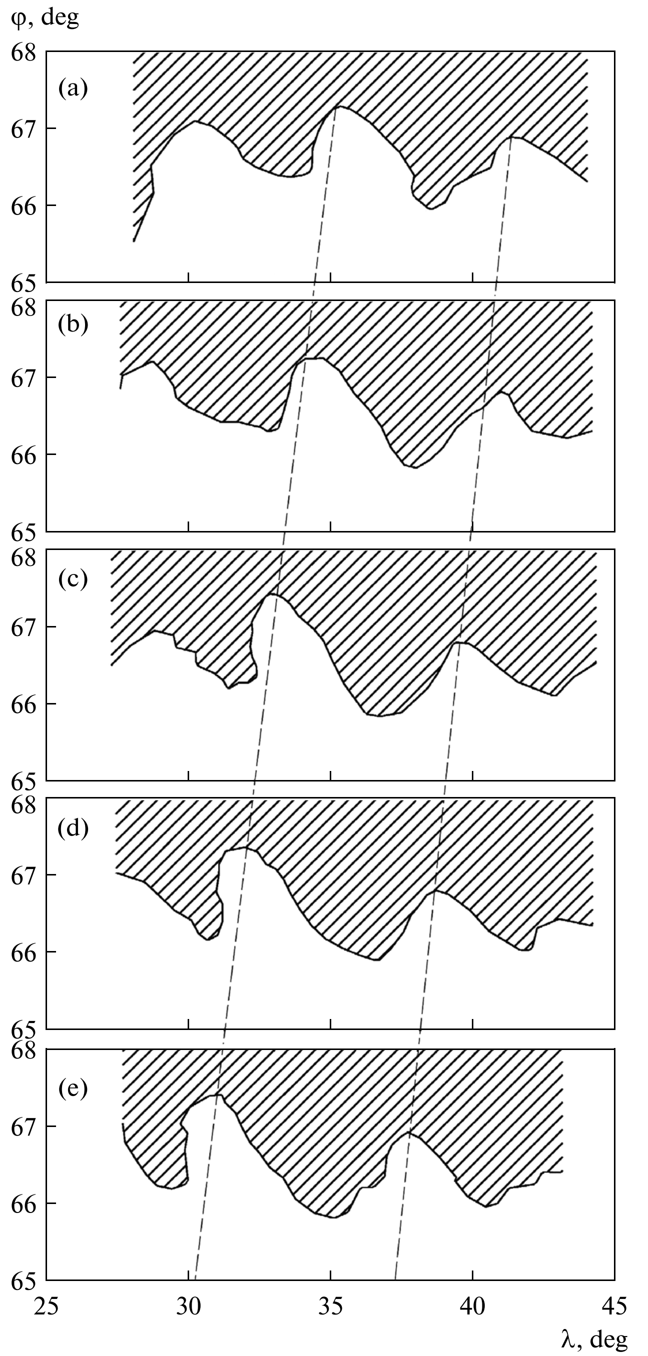

Fig. 6. Diffuse luminosity undulations in the geographic coordinate system at (a) 1445:00 UT, (b) 1446:00 UT, (c) 1447:00 UT, (d) 1448:00 UT, and (e) 1449:00 UT. The diffuse luminosity region is hatched. Two vertical dashed lines show the position of the same luminosity bays.

The LAUs considered above were observed for 2 h immediately before the maximum of a small magnetic storm with a *Dst* intensity about −50 nT. The luminosity undulation generation could be initiated by a short-living sudden impulse of the solar wind dynamic pressure. Dynamic pressure impulses were also registered before the LAU intervals considered in (Henderson et al., 2010; Baishev et al., 2000). We do not tend to consider such pressure impulses as a necessary condition for the LAU generation. However, we should note that an increase in the solar wind dynamic pressure

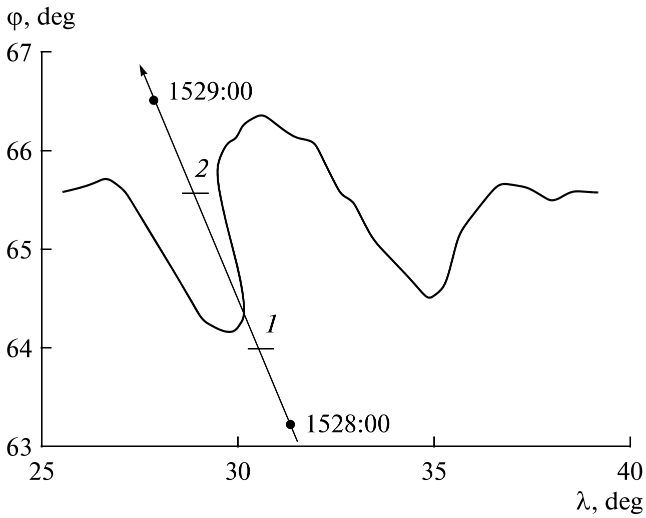

Fig. 7. Configuration of the diffuse luminosity equatorward boundary and the DMSP F16 trajectory leg. The satellite direction is shown by an arrow. Dots on the trajectory show the satellite positions at 1528:00 and 1529:00 UT. Numerals *1* and *2* show the positions of the equatorward boundaries of ion and electron precipitation, respectively.

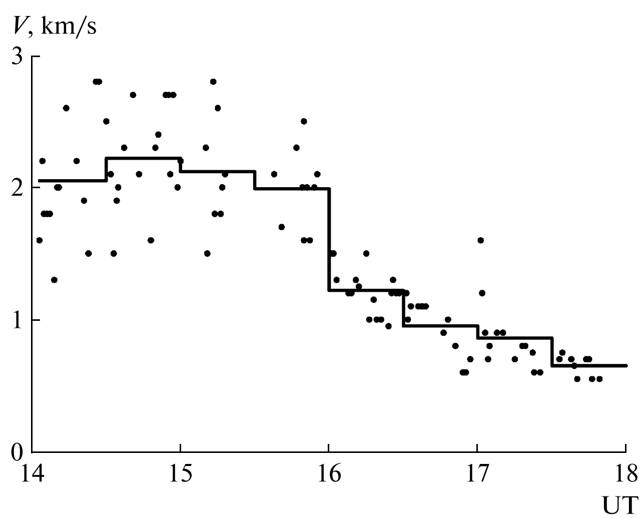

Fig. 8. Velocities of the auroral structure westward motion within the diffuse luminosity region. Solid lines show the average velocity values in each half-hour UT interval.

usually results in the intensification of auroral precipitation and in the activation of auroras in the entire auroral oval. An increase in the conductivity in the high-latitude ionosphere simultaneously with convection electric field strengthening can result in the origination of favorable conditions for the LAU generation. In the event considered in this work, the impulse of the solar wind dynamic pressure promoted a rapid transition from one stationary convection level to another level with a more intense ionospheric current system and, correspondingly, with a stronger convection electric field in the evening sector.

Some researchers (e.g., (Baishev et al., 2000; Henderson et al., 2010)) noted that LAUs were observed approximately 1 h after the onset of intense substorms. Substorm activity, i.e., the appearance of quasiperiodic substorm injections, can apparently cause the development of LAUs. If the geophysical conditions were analyzed correctly in Section 2, the SMC period that accompanied LAUs suggests that the magnetosphere and the auroral precipitation planetary pattern were factually stationary. We could assume that the azimuthal pressure gradient, which originates in the magnetosphere as a result of substorm injections, is the necessary condition for the luminosity undulation generation. Indeed, Mishin and Mishin (2007) showed that the subauroral polarization stream (SAPS) sharply intensifies and becomes structured and undulating approximately 10 min after substorm onset. These processes begin when the westward traveling surge (WTS) in the evening sector reaches adjacent SAPS in the auroral region. However, Fig. 4 indicates that the diffuse luminosity band and bright surges were also observed during other periods at different magnetic activity levels, but luminosity undulations were registered only in the image shown in Fig. 4c, when magnetospheric convection was intense. Moreover, far from all intense substorms and magnetic storms are accompanied by the appearance of LAUs. Therefore, we assume that the presence of bright surges in the diffuse luminosity poleward zone is not a necessary and sufficient condition for the development of luminosity undulations and simply indicates that activity is high in the auroral zone and, specifically, in its evening sector.

Having analyzed the different types of instabilities that could develop at the ring current outer edge and/or at the plasma sheet inner edge, Lui et al. (1982) arrived at the conclusion that the Kelvin–Helmholtz (K–H) instability can possibly cause LAU generation. This instability originates when the velocity is sheared across a certain boundary. In the LAU case such shear could be generated by westward convection in the region of diffuse auroras and by the corotation of the plasmasphere at lower latitudes. However, when Kelley (1986) analyzed the K–H instability origination conditions, he concluded that the usual velocity shear at the plasmasphere–plasma sheet boundary is too insignificant for the development of this instability. The presence of a more powerful and local plasma flow (SAPS) at subauroral latitudes is now considered the main agent resulting in the development of LAU. The performed theoretical studies (e.g., (Kelley, 1986; Yamamoto et al., 1993, 1994; Goldstein et al., 2005)) indicate that SAPS is of paramount importance in the development of the instability at the plasmapause or at the plasma sheet inner edge. Below, we will briefly analyze the experimental studies illustrated in several works (Kelley, 1986; Zhang et al., 2005; Henderson et al., 2010; Baishev et al., 2010) in order to support this hypothesis.

Kelley (1986) analyzed the LAU events detected by Lui et al. (1982) based on the DMSP photographs together with the electric field measurements on the S3-3, Explorer AE, and ISSE satellites. Kelley (1986) arrived at the conclusion that his analysis supports the hypothesis that a large velocity gradient is important for the luminosity undulation generation but is not definitive proof or a final solution of this problem, since a substantial time difference exists between the observations of LAU and electric fields in the ionosphere.

Zhang et al. (2005) studied luminosity undulations registered by the TIMED satellite in the evening sector of the Southern Hemisphere on November 20, 2003. Comparing the luminosity intensities in the atomic oxygen Lyman alpha emission with the molecular nitrogen LBH band intensity, these authors arrived at the conclusion that proton precipitation is the main energy source of LAUs. The results of the present work shown in Fig. 7 also confirm this conclusion. In (Zhang et al., 2005) the TIMED optical observations are compared with the DMSP F13 measurements of the ion drift velocity transverse component. The F13 satellite trajectory crossed the auroral luminosity region within the longitudinal interval of LAU observations but with a ~19-min difference relative to the TIMED observations.

According to the F13 satellite data, considerable ion drift velocity gradients were observed in the auroral precipitation region. However, these gradients were related to a narrow eastward jet within a wide westward convection region rather than to an increase in the westward drift velocity. Simultaneously with the ion drift velocity, F13 measured the precipitating particle characteristics. Our analysis of these data indicates that the electron precipitation equatorward boundary was at ~52° S geomagnetic latitude, which coincides with the latitude around which luminosity undulations were observed. The ion precipitation region expands equatorward by approximately 550 km farther than the electron precipitation region. This is much larger than the luminosity undulation amplitude, which was ~280 km according to (Zhang et al., 2005). Considerable velocity gradients were observed at geomagnetic latitudes of ~61°–63° S, which is poleward of the latitude where luminosity undulations are observed by approximately 10°. Moreover, the eastward convection stream, the position of which is responsible for high velocity gradients, is located in the poleward zone of intense electron precipitation, where the precipitating electron energy flux takes peak values. The presence of such a convection stream is most probably related to the bright discrete auroras at the auroral oval poleward edge.

In (Henderson et al., 2010) the optical observations of the DMSP, Polar, and IMAGE satellites were used to study in detail LAUs registered on November 24, 2001. During the ~2-h period when undulations existed, the DMSP satellites measured the ion drift velocity across the auroral precipitation zone in the evening sector. One of these F13 passes at 1515–1531 UT was considered in more detail (Fig. 13 of the cited work). These authors indicated that the westward drift velocity considerably increased at geomagnetic latitudes about 50° and called this phenomenon SAPS. Henderson et al. (2010) considered than the luminosity undulation generation results from the existence of such fast subauroral fluxes, the appearance of which can in turn be related to the fact that plasma sheet protons penetrate much closer to the Earth than electrons. At the same time, the F13 data make it possible to compare simultaneous observations of the ion drift velocity and auroral particle characteristics. Such a comparison indicates that the above increase in the drift velocity (SAPS) is observed at lower latitudes (by ~10°) than the equatorward boundary of electron and ion precipitation, which can be considered as a plasma sheet inner boundary with certain reservations.

In the LAU event studied in (Baishev et al., 2010) based on the DMSP data, considerable ion drift velocity gradients in the luminosity undulation generation region were, on the contrary, related to an unexpected appearance of a “standstill” band (the convection velocity $Vc \approx 0$) near the poleward edge of intense electron and ion precipitation rather than to an enhanced convection stream. Such a behavior of the drift velocity and auroral precipitation characteristics can correspond to the transition from the diffuse luminosity region to bright discrete auroras at the poleward edge of this region. In this case we should take into account that a substantial longitudinal difference exists between the DMSP satellite trajectory and the location of Tiksi observatory, the optical observations at which were used in (Baishev et al., 2010).

Thus, with a lapse of almost two decades, we can repeat the conclusion made in (Kelley, 1986) that the performed experimental studies are not definitive proof or a final solution of this problem, although they to a certain degree support the hypothesis that SAPSs are important for the luminosity undulation generation.

It is apparently necessary to perform additional experimental and theoretical studies in order to understand the nature of LAUs. In this case the theory, not necessarily one that relies on considerable drift velocity gradients, should describe the main LAU characteristics, e.g., the luminosity undulation westward motion at a velocity of ~0.7 km/s and the fact that LAUs are mostly related to proton precipitation. (Fedorovich, 1988) can be an example of a theory that does not use velocity gradients. This author proceeds from the assumption that low-frequency (LF) drift waves propagating along the plasma sheet (PS) constantly exist in this sheet. If the convection electric field is strong, these waves propagate to the PS inner boundary, where they are transformed into surface waves the wavelength of which increases in the course of time.

5. CONCLUSIONS

We studied the optical characteristics of LAUs observed with the all-sky cameras on the Kola Peninsula on December 28, 2010, and analyzed the corresponding conditions in the interplanetary medium and geomagnetic activity characteristics. We showed that the appearance of luminosity undulations could be initiated by the solar wind dynamic pressure impulse and their existence for 2 h was supported by the SMC electric field. The luminosity undulation altitude, determined using the triangulation method, was 120 ± 10 km. The undulation amplitude varied from ~100 to 300 km, and the average wavelength was ~250 km. Luminosity undulations moved westward at an average phase velocity of ~0.7 km/s. The F16 satellite pass along the luminosity tongue indicated that the luminosity undulation was located in the region of only ion (proton) precipitation, the average energy of which was ~18 keV. Rayed structures moving westward at an average velocity about 2 km/s, which corresponds to the northward electric field (~100 mV m^{-1}), were continuously observed in the diffuse luminosity region. A rapid decrease in the rayed structure velocity was accompanied by a damping and complete disappearance of LAUs. An analysis of the experimental results presented in several works on this subject matter showed that it is necessary to continue experimental and theoretical studies in order to understand the nature of LAUs.

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