A Flight of the Proton-M Launch Vehicle Carrying the Yamal-601 Satellite: Optical Effects Observed in a Distant Zone of the Launch Site

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Abstract—In this paper, we consider disturbances in the airglow of the Earth’s upper atmosphere caused by a launch of the Yamal-601 satellite on May 30, 2019. For this purpose, we used the data acquired with an optical system of the Institute of Solar−Terrestrial Physics, Siberian Branch, Russian Academy of Sciences (ISTP SB RAS). The measurements were carried out at the Geophysical Observatory (GPO) of the ISTP SB RAS (~52° N, ~103° E) with a complex of optical instruments—a whole-sky camera, a spectrograph, and a Fabry−Pérot interferometer. According to the data of the KEO Sentinel camera, an extensive area of airglow was observed along the flightpath; it appeared approximately 2−4 min after the spacecraft’s passage over the GPO and existed for ~20 min. A transversal scale of the spacecraft’s flightpath is estimated approximately as 95–110 km if the spontaneous-emission altitude is assumed to be at ~150 km (and it is about 190–220 km if the spontaneous-emission altitude is ~300 km). We discuss the mechanisms that may result in forming the observed area of airglow, including the mechanisms connected with the physical and chemical interaction of fuel products with atmospheric components and the influence of propagation of a shock wave or short-period internal gravitational waves. Probable causes of the delay observed in appearing the airglow after the spacecraft’s flyby are analyzed.

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INTRODUCTION

Technogenic activity at the altitudes of the ionosphere and thermosphere makes it necessary to monitor and determine its impact on the characteristics of the upper atmosphere. Among the most representative examples of works of this kind are active experiments on the ionosphere heating [15] and injections of “plasma-quenching” mixtures by geophysical rockets [1], launches of spacecraft (SCs), and operation of their engines during maneuvers on the orbits [5, 20–25]. One of the manifestations of technogenic activity is disturbances in the airglow of the upper atmosphere, which are caused by SC launches and active experiments at orbital altitudes, and they are superimposed onto natural variations in the emissions of the upper atmosphere [9, 23]. Because of this, it is necessary to study the morphology and the mechanisms of disturbances induced by technogenic activity in the airglow of the upper atmosphere against the background of natural variations.

In papers [2, 9], the results of optical observations in the Radar-Progress space experiment were presented. During operation of the approach-correction engines at the altitudes of the thermosphere, the areas of enhanced emission, which are presumably related to the background radiation scattering on exhausts of the approach-correction engines and/or the extra emission appeared in the atomic-oxygen line [OI] at 630 nm, were observed.

In this paper, we present the results of optical observations of the flight of the Proton-M launch vehicle (LV) carrying the Yamal-601 satellite, which were performed in a far-field zone of the launch site.

INSTRUMENTATION AND OBSERVATIONAL TECHNIQUE

The emission of the upper atmosphere is observed at the Geophysical Observatory (GPO) of the Institute of Solar−Terrestrial Physics, Siberian Branch, Russian Academy of Sciences (ISTP SB RAS) (~52° N, ~103° E), located in the Tunka valley in the south of Eastern Siberia. The GPO complex of optical and radiophysical instruments includes spectrographs, a Fabry−Pérot interferometer, multicolor and monochromatic wide-angle cameras, and an ionosonde. In this study, we use the data of observations with a whole-sky KE0 Sentinel camera, a Fabry−Pérot interferometer, and a SATI-1M spectrograph.
The whole-sky KEO Sentinel camera is designed to register the spatiotemporal dynamics in the intensity of the 630-nm emission (the spontaneous-emission altitude is 180–300 km). The half-width of the interference filter is ~2 nm. The viewing direction is zenith, the field of view is 145°, and the exposure time is 60 s (http://atmos.iszf.irk.ru/ru/data/keo).

The SATI-1M spectrograph is designed to register the intensity of dominant emissions in the nightglow spectrum of the ionosphere—atomic oxygen [OI] at 557.7 and 630.0 nm and a nitrogen doublet Na [OI] at 589.0–589.6 nm—for investigating the processes in the upper atmosphere during helio- and geophysical disturbances of various nature (http://atmos.iszf.irk.ru/ru/data/spectr).

The Fabry−Pérot interferometer is designed to measure the intensity of atmospheric emissions, the atmospheric temperature, and the wind speed at spontaneous-emission altitudes. The measurement technique is based on registering the Doppler shift and the Doppler broadening of nightglow lines. The observations are made at fixed wavelengths related to emissions of atomic oxygen [OI] at 630 and 557.7 nm and nitrogen Na at 589.3 nm, the first negative band of ion of molecular nitrogen N₂ 1NG (0-1) at 427.8 nm, oxygen ion [OII] at 732.0 nm, and the 843.0-nm band of hydroxyl OH (6-2). This instrument is described on the website http://atmos.iszf.irk.ru/ru/data/fpi.

OPERATIONAL AND TECHNICAL CHARACTERISTICS OF THE PROTON-M LAUNCH VEHICLE AND BRIZ-M ROCKET BOOSTER. STANDARD FLIGHT SEQUENCE

The Proton-M LV with the Briz-M rocket buster (RB) and the Yamal-601 SC was launched at 17:42 UT on May 30, 2019 (https://www.roscosmos.ru/26339/). The Proton-M is a heavy-class launch vehicle. Its start weight is about 705 t; it has three stages; for propellant components, unsymmetrical dimethylhydrazine and nitrogen tetroxide (UDMH + NT) are used; and the payload mass including the Briz-M RB is 6.3 t (https://www.roscosmos.ru/465/).

The Briz-M RB is used as a component of the Proton-M and Angara-A5 LVs to insert a payload into low-Earth orbits of various heights and inclinations. Its start weight is up to 22.5 t, the onboard fuel supply is up to 20 t, the fuel components are UDMH and NT, and the sustainer engine can be switched on up to eight times (https://www.roscosmos.ru/450/).

Table 1 presents a standard sequence of the Proton-M LV with the Briz-M RB (https://aboutspacejornal.net/Космические-аппараты/ракета-носитель/протон/).

| Lift Key command                          | 0.0 | 465 | 11 |
|------------------------------------------|-----|-----|----|
| Reaching maximum velocity head           | 65.5| 1724| 42 |
| Switching on second-stage motors         | 119.0| 123.4| 42 |
| Division of first stage                   | 332.1| 335.2| 120|
| Activation of third-stage steering motors| 334.5| 337.6| 123|
| Switching off second-stage motors         | 348.2| 576.4| 151|
| Separation of second and third stages     | 588.3| 588.4| 151|
| Head fairing reset                        | 7182| 111|

The Initial Segment of Briz-M RB Operation

Immediately after separation of the third stage of the Proton-M LV, the RB stabilization engines are switched on, which ensures the orientation and stabilization of the orbital block (OB) in the passive flight segment along the suborbital trajectory until the first activation of the RB engine. Approximately one-and-a-half minute after separating from the LV, the sustainer engine is activated for the first time for 4.5 min, which results in the formation of a reference orbit with a height of 170–230 km and an inclination of 51.5° (https://aboutspacejornal.net/Космические-аппараты/ракета-носитель/протон/). According to the flight sequence above, at the beginning of the solo flight of the Briz-M RB, its height is approximately 150 km.

RESULTS OF OBSERVATIONS

KEO Sentinel Camera

Figure 1 shows fragments of the original images taken by the KEO Sentinel camera within a time interval of 17:52–18:11 UT. Figure 2 presents complete images for a time interval of 17:51–18:17, which were
processed with the method described in paper [4]. Image processing was done as follows: the reference frames were subtracted with the weights depending on the time interval between the reference frame and the analyzed image, and the contrast of the images was further enhanced. To choose the reference frames, the time intervals before and after the flight of the space object (SO) were used, i.e., these images contained no visible signs of the influence of the SO. In the images taken at ~17:53, a flyby of the SO is seen, which can be associated with the Proton-M LV overflying the GPO. In this case, the delay in detecting the LV above the GPO relative to the LV takeoff from the Baikonur site is ~660 s. This delay value is apparently typical of the heavy-class LVs for the distance between Baikonur and the GPO [8].

In correspondence with the standard flight sequence of the Proton-M LV, by that time, the third-stage motors had been turned off and the third stage had been separated from the orbital block (~588 s). Immediately after separating the third stage of the LV, the Briz-M RB stabilization engines are switched on. Approximately one-and-a-half minute (~90 s) after separation from the LV, the sustainer engine of the RB is switched on for the first time for 4.5 min, which results in forming a reference orbit of the OB. Thus, the sustainer engines of the Briz-M RB could be activated approximately at 17:53 UT, which is 17:42 UT (the takeoff moment) plus (588 + 90 s), i.e., ~11 min. This time moment corresponds to that of the image of the track in Fig. 1. Taking this circumstance into account, we may suppose that the event registered at the GPO at 17:53 UT was a flight of the Yamal-601 satellite with activated engines of the Briz-M RB. Beginning from a moment of ~17:56 UT (with a delay of about 2–4 min after the SO flyby), an extensive area of airglow was formed along the SO flightpath; and it was observed for more than 20 min (until ≥18:17 UT).

In the images taken by a multicolor camera, which is installed at the Sayan Solar Observatory located 150 km west of the GPO [10], the effects shown in Fig. 1 were not found. At the same time, it should be noted that, in two images taken by this camera at about 18:01–18:03 UT, there is a dotted track of the SO moving in the east direction.

Fig. 1. Fragments of original images taken by the KEO Sentinel camera within a time interval of 17:52–18:11 UT.
In Fig. 3, we show variations in the atmospheric emissions [OI] at 557.7 and 630.0 nm (the spontaneous-emission altitudes are approximately 85—115 and 180—300 km, respectively) registered during the night of May 30—31, 2019. According to the standard flight sequence of the Proton-M LV, when the third stage of the LV (roughly within a period between seconds 335 and 588 of the flight), the LV trajectory was at altitudes of approximately 120—150 km, while the orbital speed was about 4.5—7.2 km/s. A supersonic flight of an SO at these altitudes may result in formation of shock and acoustic—gravitational and internal gravitational waves (IGWs), which leads to variations in the characteristics of the upper atmosphere and the ionosphere [5]. What is noteworthy in Fig. 3 is the behavior of the emission intensity at 557.7 nm in a time interval of about 18—19 UT, probably indicating the manifestation of a wave of the IGW type. It should also be noted that different sources are considered as related to manifestations of IGWs in the emission of the upper atmosphere, which are observed rather often [14].

**SATI-1 Spectrograph**

**Fabry—Pérot Interferometer (FPI)**

The atomic-oxygen emissions [OI] at 557.7 and 630.0 nm (the spontaneous-emission altitudes are approximately 85—115 and 180—270 km, respectively) were measured with the Fabry—Pérot interferometer on May 30, 2019. According to the standard flight sequence of the Proton-M LV, the latter was at altitudes of about 120—150 km when overflying the GPO. This does not allow us to use directly the FPI data about the temperature and the wind conditions in the atmo-
sphere at the altitudes of the Proton-M LV passage; however, the data can be used to estimate probable vertical and horizontal motions or determine their absence. In particular, in a time interval of 17:52–18:11 UT, at altitudes of about 85–115 km, the meridional and vertical velocities were ≤25 and 10 m/s, respectively, while they were ≤120 and 15 m/s, respectively, at altitudes of about 180–270 km.

DISCUSSION OF OBSERVATION RESULTS

Optical phenomena occurred in the upper atmosphere and related to emissions of combustion products of rocket engines were classified in paper [13]. The analysis revealed several main types connected with different geophysical conditions and mechanisms of their formation. Naturally, the altitudes at which combustion products are injected and the optical formations are observed became one of the main criteria for classifying optical phenomena, since the physical conditions, rather strongly varying with altitude, determine different spatial, temporal, and spectral characteristics of the optical formations. For example, the optical phenomena developing in the stratosphere, at altitudes of 40–50 km, typically exist for a relatively long time, their brightness is high, the sizes are rather small, and the diffusion and stratospheric winds are of key importance for them. Starting from the turbopause altitudes, from about 100–120 km and higher, there are conditions for developing optical phenomena, the emission mechanisms of which are the light scattering on a disperse phase of the combustion products; the interaction of combustion products of LV engines with components of the upper atmosphere, which may induce the formation of ionospheric holes (the ionosphere alterations); and resonance scattering of solar radiation.

At the same time, it is well known that the formation of ionospheric holes is accompanied by strengthening the forbidden emission of atomic oxygen [OI] at 630.0 nm [23, 24].

Based on the characteristic lifetimes and spatial sizes of the observed optical phenomena under discussion, we may preliminarily consider two main mechanisms that cause the optical effects observed. The most frequently discussed mechanism, which is related to the SC flight at initial sections of the trajectories, is caused by the light scattering on combustion products of the LV engines [1, 13]. One more mechanism is connected with strengthening the intrinsic emission of the upper atmosphere under alteration of the ionosphere induced by interaction of the combustion products with the atmospheric components (see, e.g., [12, 22]). It is possible that the second mechanism might be activated, because the airglow area was registered by the whole-sky KEO Sentinel camera in a relatively narrow spectral band (~2 nm) centered at a wavelength of 630.0 nm. In this regard, here, we pay some attention to the consideration of a possible mechanism of initiating the atmospheric emission of atomic oxygen [OI] at 630.0 nm.

Spatial and Temporal Dynamics of Disturbances

According to the KEO Sentinel camera data, the airglow area began forming in approximately 2–4 min after the SC flyby over the GPO and existed for more
than 20 min. A transversal spatial scale the SC flightpath is approximately estimated as 95–110 km, if the spontaneous-emission altitude is assumed to be ~150 km (and it is about 190–220 km if the spontaneous-emission altitude is ~300 km).

The fact that the airglow area appeared with a delay of about 2–4 min after the SC passage over the GPO may suggest that there was no effect of the light scattering at the combustion products (the angular immersion of the Sun beyond the horizon, i.e., the nautical twilight, was ~11°), at least for the first minutes after the SC passage. A delay in the appearance of irradiating formations is noted in a number of papers describing active experiments [17, 18]. For example, according to [18], after the injection of ~2.7 \times 10^{26} and 7.4 \times 10^{26} molecules of CO₂ and H₂O, respectively, into the ionosphere at an altitude of ~323 km, a disturbed irradiating area was formed. Two minutes after the injection, the 630-nm emission increased up to 400 R; in 3 min, the area of enhanced emission reached 250 km in diameter. At the same time, in the Radar-Progress experiment, at thermosphere heights, no analogous time delay was detected [2, 9]. Unfortunately, the papers dealing with active experiments pay almost no attention to the initial stage in the development of the optical effects. Among possible causes of this delay, we may mention the time required for thermalizing hot fuels with atmospheric components, resulting in changes of the rate of physical and chemical reactions, and the spreading of injection products to the other heights caused by, for example, the diffusion, the possible spreading of combustion products laterally relative to the SC flightpath [9, 13], and the drifting of combustion products by height due to vertical winds.

Diffusion

In its classical version, diffusion occurs at the molecular level in the atmosphere and becomes essential as a transfer process only in the thermosphere. At lower altitudes, the main transfer process is associated with motions of air volumes and, consequently, with turbulent diffusion. According to [7], at a lower boundary of the thermosphere, the diffusion coefficient is \( K_D \approx 10^3 \) m²/s and linearly decreases with altitude. The highest values of the turbulent diffusion coefficient are \( K_{TD} \approx 10^2-10^3 \) m²/s [3, 16].

\[
R = (4K_D \times t)^{1/2}.
\]

(1)

For the considered event at a moment of ~360 s (when the main the airglow area has been formed) and the value \( K_D \approx 10^3 \) m²/s, expression (1) yields ~1.2 km for the characteristic size of the diffuse spreading. This value is substantially smaller than the horizontal sizes of the observed airglow area estimated from the data of observations with the whole-sky KEO Sentinel camera.

Suprathermal-Velocity Dispersion of Fuel-Combustion Products

It is known that transverse (specifically, vertical) velocities of dispersing the combustion products relative to a SC flightpath may reach values higher than 1–3 km/s [9, 13]. Due to these dispersion velocities, the combustion products may rather quickly move to the F-region of the ionosphere, within which there are more favorable conditions for forming the [OI] emission at 630.0 nm in dissociative-recombination reactions. For example, for a velocity of ~1 km/s, from an altitude of ~150 km to an altitude of ~270 km, the corresponding dispersion time is ~120 s, which is comparable to the delay observed in appearing the airglow area, 2–4 min. In this case, the upward spreading of combustion products will be most advantageous due to a larger free path (since the atmospheric density decreases with increasing the altitude). This mechanism of producing airglow does not exclude that light scattering may occur on the fuel injection products when they move to upper levels.

Wind Drift of Fuel-Combustion Products

If the wind drift is taken into account, the dynamics in the development of optical effects is determined by the current wind conditions. For the analyzed case, these conditions can be estimated from the data of observations with a Fabry–Pérot interferometer (see above). For a time interval of 17:52–18:11 UT, at altitudes of about 85–115 km, the meridional and vertical velocities, which are integrated over spontaneous-emission altitudes for the lines at 557.7 and 630.0 nm, were ~25 and 10 m/s, respectively, while they were ~120 and 15 m/s, respectively, at altitudes of about 180–270 km. In Table 2, the characteristic values for drifts of fuel-combustion products are shown for the time moment at ~360 s after the SC passage.

It is seen from Table 2 that significant drifts (~43 km) may be provided by meridional winds at altitudes of about 180–270 km. According to the KEO Sentinel camera data, the transversal scales of the airglow area of the SC flightpath are estimated as ~200 km for these altitudes. However, it should be realized that meridional winds of the same direction can only move an airglow area as a whole rather than participate in forming its meridional sizes. The observed insignificant vertical displacements, which are caused by vertical winds, also cannot apparently induce the formation of an airglow area due to considerable changes of physical and chemical parameters with altitude in the region of injecting fuel-combustion products.
The rate of gas-kinetic collisions at altitudes of 180, 270, and 350 km is ~0.8, 0.08, and 0.02 s⁻¹, respectively [14]. Consequently, the time for thermalization and physical and chemical interaction of the fuel-combustion products with the atmospheric components (from one to three collisions) at the mentioned altitudes may approximately amount to 1.25–3.75, 12.5–37.5, and 50–150 s, respectively. This makes it possible to assume that the effects of thermalization and physical and chemical interaction of fuel-combustion products at altitudes larger than 270 km may contribute to the delay between the moment of fuel injection and the moment of airglow occurrence, which is comparable to the observed delay, of about 2–4 min.

**Possible Mechanisms of Forming the Observed Airflow Area**

Several mechanisms of the appearance of airglow formations in the upper atmosphere, which are related to a flyby of an SC with activated engines, are currently under discussion in the literature. Among them, we may note alteration of the ionosphere resulting from interaction of fuel-combustion products with components of the upper atmosphere, the generation of shock waves and IGWs that appear during an SC supersonic-speed flight in the neutral atmosphere, the emergence of waves and instabilities in the ionospheric plasma induced by missile plumes, and light scattering on a disperse phase of combustion products (see, e.g., [5, 23, 24]). Apparently, in many cases, the above-mentioned mechanisms simultaneously participate in the formation of atmospheric airglow, and their contributions to the overall effect may differ and depend on the altitude, types of injected products, and other geophysical conditions [13]. Since the range of issues connected with the interaction of injected compounds with the upper atmosphere is rather wide, they cannot always be analyzed at length within the frames of one paper. Below, we consider one of the likely mechanisms causing the occurrence of an airglow area—the physical and chemical interaction of fuel products with the atmospheric components.

The *Briz* RB propellant has two components: nitrogen tetroxide N₂O₄ (an oxidizing agent) and UDMH fuel (unsymmetrical dimethyl hydrazine C₂H₈N₂) (https://www.roscosmos.ru/450/).

In a probable reaction of oxidation of the UDMH fuel by nitrogen tetroxide,

\[
\text{C}_2\text{H}_8\text{N}_2 + 2\text{N}_2\text{O}_4 \rightarrow 3\text{N}_2 + 2\text{CO}_2 + 4\text{H}_2\text{O},
\]

molecules of carbon dioxide CO₂ and water H₂O are produced. At ionospheric altitudes, they may participate in charge-exchange reactions, producing O₂⁺ and H₂O⁺ ions according to the following reactions [19, 24]:

\[
\begin{align*}
\text{CO}_2 + \text{O}^+ & \rightarrow \text{O}_2^+ + \text{CO}, \\
\text{O}_2^+ + \text{e} & \rightarrow \text{O} + \text{O}^1\text{D}, \\
\text{H}_2\text{O} + \text{O}^+ & \rightarrow \text{H}_2\text{O}^+ + \text{O}, \\
\text{H}_2\text{O} + \text{O}^+ & \rightarrow \text{H}_2\text{O}^+ + \text{O}^1\text{D}.
\end{align*}
\]

In these reactions, atomic oxygen in the ¹D state is produced, which leads to the emission of a photon at 630.0 nm according to the reaction

\[
\text{O}^1\text{D} \rightarrow \text{O}^3\text{P} + \hbar\nu(630 \text{ nm}).
\]

It is well known that O₂⁺ and H₂O⁺ ions rapidly recombine with free electrons in the ionosphere, with the dissociative-recombination rates in reactions involving these ions (substitution reactions) being several orders of magnitude higher than the dissociative-recombination rates in reactions involving O₂⁺ and H₂O⁺ ions in natural conditions. These processes are accompanied by intensified filling of the O¹D level of atomic oxygen and enhance the [OI] intensity at 630.0 nm [11, 23, 24]. For example, as follows from the estimates made in a paper [11], the efficiency of atomic oxygen transition into the ¹D state in reactions with participation of CO₂ molecules at ionospheric altitudes may be more than 300 times higher than that in natural conditions. Though the dissociative-recombination rates in substitution reactions are high, it is necessary to take into account the efficiency of reaction (7) at different altitudes. The fact is that the radiative lifetime of the excited ¹D state of atomic oxygen is about 110 s. Under the real condition of the lower thermosphere, excited atoms of O¹D may be deactivated, emitting a photon at 630.0 nm in collisions with molecules of the atmosphere—mainly, O₂ and N₂, according to the following reactions [14]:

\[
\begin{align*}
\text{O}^1\text{D} + \text{N}_2 & \rightarrow \text{N}_2^8 + \text{O}^3\text{P}, \\
\text{O}^1\text{D} + \text{O}_2 & \rightarrow \text{O}_2^8 + \text{O}^3\text{P}.
\end{align*}
\]

Since the rates of these deactivation processes are rather high, the prior-to-emission losses of exited atoms O¹D sharply grow with decreasing altitude. It is against this background that, in the emission at 630.0 nm, the natural emission layer of atomic oxygen has a lower boundary around 180–200 km (if the

| Altitudes, km | Vertical drift, km | Meridional drift, km |
|--------------|-------------------|---------------------|
| 85–115       | −3.6              | −9                  |
| 180–270      | −5.4              | −43                 |

Table 2. Characteristic values for the drifts of fuel-combustion products for a time moment of ~360 s
The radiation lifetime of the excited 1D state. These values may be used to estimate the efficiency of reaction (7) at different altitudes by ratios of the inverse values of the gas-kinetic collision rates to the radiation lifetime of the excited 1D state. These ratios are ~0.01, 0.1, and 0.45 for considered altitudes of ~180, 270, and 350 km, respectively. If this ratio is close to unity, the probability of reaction (7) is close to 100%. The above estimates allow us to suppose that the considered mechanism of emission at 630.0 nm in reactions (2)–(7) is most effective at altitudes above 270 km. It is worth noting here that the analogous altitude values have been also obtained before when estimating the time delay in occurrence of the airglow after the injection of combustion products.

With regard to a possible impact of propagation of a shock wave or short-period IGWs on the effects observed approximately between 17:56 and 18:17 UT, we may say the following. The detected optical disturbance is a relatively stable formation that contains no quickly moving irradiating local zones, which is typical of a shock-wave front or crests of short-period IGWs; consequently, its spatiotemporal dynamics makes it difficult to use the above-described wave mechanisms for tentative interpretations of the optical effect observed. To do this, it will apparently be necessary to perform additional studies based on new data of observations and model calculations.

CONCLUSIONS

Based on the data presented above about the optical observations carried out during a flyby of the Proton-M LV with the Briz-M RB over the Geophysical Observatory of the ISTP SB RAS on May 30, 2019, we have arrived at the following preliminary conclusions.

According to the observations with the KEO Sentinel camera, an extended airglow area was registered approximately between 17:56 and 18:17 UT along the flightpath of the Briz-M RB of the Proton-M LV over the GPO. The most probable region of forming the extended airglow area was at altitudes where the Briz-M RB of the Proton-M LV was moving over the GPO and higher (the altitudes of a lower part of the F2 ionospheric layer).

Since the airglow area was detected by the camera in the spectral band centered at a wavelength of 630.0 nm, we considered one of the airglow-formation mechanisms, which is connected with the atmospheric emission at 630.0 nm excited by interaction of fuel-combustion products with atmospheric components. Analysis took into account the fuel composition used for the Briz-M RB. The combustion reaction for the main components of the Briz-M RB fuel is accompanied by the formation of carbon dioxide CO2 and water H2O molecules, which may participate in producing O2 and H2O+ ions at the ionospheric altitudes. In the charge-exchange and dissociative-recombination reactions producing these molecules and ions, oxygen atoms in the 1D state are formed, and transition from this state to the ground one is accompanied by emission at a wavelength of 630.0 nm. In this case, we may probably say that there is some alteration in the composition of the atmosphere and ionosphere in a relatively extended area near the flightpath of the Briz-M RB, which revealed itself in the emission of atomic oxygen [OII] at 630.0 nm.

Probable causes of a delay of approximately 2–4 min observed in the appearance of the airglow after the Briz-M RB passage were considered. The behavior of the intensity in the 557.7-nm emission at ~18:19 UT apparently suggests that an IGW-type wave arrived from the Proton-M LV, flying in the distant zone of the GPO, or from the Briz-M RB, flying directly over the GPO.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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