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Atmospheric Optical Phenomena Caused by Powerful Rocket Launches

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Results are presented of observations of artificial optical effects in the atmosphere that were made mainly by means of all-sky cameras in northwest Russia and Scandinavia. There were six artificial optical effects observed during 10 years of observations made simultaneously from two or three stations and five more from single stations. One of the cases was registered by a television camera on Heiss Island (Frantz-Joseph Land), and these observations allowed assumptions to be made on the volumetrical shape of the phenomena. It was assumed to have a toruslike form rather than a spherical shape, and the luminosity was caused by Rayleigh scattering of sunlight by particles, which formed a gas and dust cloud during the launch of a rocket. Observations from distant points were used to make triangulation measurements. It was shown that all of the observed phenomena had both common and original features. The altitudes of luminosity for different cases varied from 230 to 1080 km. The clouds represented rapid horizontally expanding circular objects with the front edge propagation velocity of 3–7 km $\cdot s^{-1}$. Diametrical sizes of luminous clouds in some cases exceeded 1600 km at later stages of their development. Five of the six phenomena, the sizes of which were measured by triangulation, were most likely caused by launches from the Plesetsk rocket range in northwest Russia, whereas the remaining one apparently was launched from a place located in west of the Kazakh republic. The possibility of observations of such types of phenomena depends very much on sunlight conditions, direction of launch trajectory, and weather conditions.

Introduction

THE influence of rocket launches on the ionosphere was identified from the very beginning of space and near-Earth environment investigations by satellites and powered rockets. Booher[1] first postulated that powered rocket flights through the F-region produces an extensive ionospheric hole, which persisted up to the order of one-half hour subsequent to the firing of Vanguard II in 1959. Later this was confirmed repeatedly. It was found that the ionosphere could be disturbed in a wide range of altitudes, whereas a disturbed region could exist for a time much longer than the time of rocket flight with the burning vehicle.[2–4]

One of the most informative launches was that of Skylab by the Saturn V carrier in 1973,[5,6] which initiated a rapid and large-scale depletion of the ionosphere to an extent never seen before. Simulations of physical and chemical processes, based on the reaction of H_2 and H_2O molecules with atmospheric species leading to high rates of recombination processes of electrons and positive ions in the ionosphere and consequently causing ionospheric holes, were carried out.[7] These studies initiated the use of rocket launches for practical scientific purposes in radio astronomy as providers of artificial ionospheric windows for observation of low-frequency waves.[8,9] Further investigations of the ionospheric reaction to rocket launches confirmed the results obtained previously and are summarized in Ref. 10. It was shown that launches of powerful rockets such as Apollo and Soyuz-19 in the Soyuz–Apollo program[11] and Saturn V in the Skylab program[5,6,9] could cause ionospheric disturbances at distances exceeding 2000 km from the launching place. The disturbances could cover an area of about 1×10^6 km^2 existing for several hours after the launch time, whereas the total electron contents could decrease to about 50%. Generation and propagation of wave disturbances in the ionosphere[12] and excitation of atmospheric emissions[13] provided by the interaction of exhaust gases with ionospheric constituents were observed in addition to the ionospheric holes.

From the earliest days of the former U.S.S.R. and U.S. space programs great attention has been paid to the subject of possible contamination and pollution of the upper atmosphere by rockets. At its meeting in Prague in October 1962, the Executive Council of the International Council of Scientific Unions (ISCU) adopted a resolution that noted that the large rockets used in the connection with satellites and space vehicles could introduce into space and the upper atmosphere matter that could possibly have an adverse effect on future scientific observations and that could possibly change the natural state of the atmosphere. In 1963 at the request of ISCU, the Consultative Group of the Committee on Space Research (COSPAR) agreed to study the matter of pollution and prepared a technical note on the subject. Kellogg[14] published a comprehensive review of the subject based on the prepared draft note as well as comments from many knowledgeable scientists. Many possible ways that rocket pollutants could impact the atmosphere were considered in this review. The problem was defined as follows: What is the maximum number of large rockets that can be launched per year without causing a widespread change in the upper atmosphere that is larger than the natural variations that already exist? The result of the

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back-of-the-envelope calculations was that about 1000 superrockets are required to double the natural concentration of upper atmosphere constituents such as H_2O, CO_2, and NO. The main conclusion was that if the result had been correct "it should allay the fears of those who have worried about polluting the upper atmosphere with the exhaust from our big rockets."[14]

Mendillo et al.[9] reported, 15 years after Kellogg's[14] assessment, that hardly a dozen accounts exist describing specific aeronomic perturbations associated with the many hundreds of rocket launches that have occurred since the launch of Sputnik-1 in 1957. The authors explained the low number of accounts as follows: 1) prevailing amount of small rocket launches; 2) majority of large rocket launches carrying payloads into low Earth orbit ($h < 200$ km), where the typical exhaust products were H_2O, H, CO, N, and O, relatively inconspicuous additions to ambient conditions; and 3) location of large rockets trajectories launched by U.S. agencies over water. The main conclusion was that virtually all past rocket launches offered little reason to search systematically for the atmospheric perturbations caused by rocket effluents.

A different opinion was expressed by Krassovsky et al.,[13] who noted that water is detained in the upper atmosphere for a long time after powered rocket launches. They showed that the level of atmospheric hindrances for the frequency of 27 kHz considerably increased (to ~10 dB) 7–8 days after Skylab launch and retained for about 1.5 months. The authors explained it as moistening of the atmosphere at lower D-region altitudes.[15] It was concluded that one could expect that the state of the ionosphere, as a consequence of such types of human activity, would constantly change.

All of the mentioned results were obtained using radio methods such as Faraday rotation measurements and ionosonde vertical sounding. This paper is devoted to optical observations of atmospheric effects caused by launches of large rockets.

Launches of powered rockets and operation of spacecraft vehicles, which are accompanied by releases of gas, plasma, and disperse particles of various sizes at various altitudes, lead to the development of artificial gas and dust cloudlike formations. These formations scatter the sunlight or, reacting with chemical species of the atmosphere, cause a luminosity, which results in extraordinary optical phenomena in the surrounding space of the Earth.[16] Although in most cases they can be seen easily with the naked eye, documentation is rare. Most of them were accounted for in the proceedings of a number of recent conferences devoted to atmospheric optics and spacecraft and rocket interactions with the surrounding environment.[17–21]

Vetchinkin et al.[22] observed optical effects caused by launching of the Molniya satellite by the Soyuz carrier. They determined that the altitude of the phenomenon varied in the range from 120 to 180 km. The expansion velocity of the exhaust gases was 1–2 $km \cdot s^{-1}$. The maximum observed horizontal size of the artificial formation just after engine cutoff was 390 km. They also reported observations of UV emissions at $\lambda = 275.0$ nm from a UV imager telescope at the astrophysical station (AS) Astron after the launch of the space shuttle on 3 February 1984. It was shown that 3.5–4.5 h after the launch, a region with increased UV emission was registered along the trajectory of the rocket. The intensity of the UV emission reached 60% above background level. The diametrical dimension of this region was about 1000 km. AS Astron was at a distance of 40,000 km from the enhanced region at that time. A similar increase of UV emission (up to 60–100% above background level) was registered also after the launch of the Proton rocket on 29 March 1984.

Investigations of visual artificial formations of dispersed particles that accompany rocket launches and operation of spacecraft vehicles is important from the points of study of diffusion processes dynamics in the Earth's atmosphere at various altitudes,[20,23] problems of atmospheric optics,[22,24] space pollution, the influence on ozone contents[25] mentioned earlier, and estimating real sizes of the artificial influence of rocket launches on the atmosphere.[13,26]

All observations carried out previously were mainly occasional and made by various methods, which makes it difficult to compare to and find common or different features of the phenomena. This paper is based on the results obtained by standard equipment, during a long time interval, in the same area, on the basis of a great amount of routine photographic pictures of the sky obtained by the net of all-sky cameras located in northwest Russia, Finland, and Northern Scandinavia.

Database

All-sky cameras were designed in the 1950s before the International Geophysical Year to obtain photographs of the whole night sky in a program that was common for most of the auroral observatories in the world. Furthermore, these data were used for making global pictures of auroral displays. Usually a single camera made one picture per minute. Exposure times can be different, varying from 2 to 20 s, depending on the brightness of the aurora and the sensitivity of the film.

The brightness of atmospheric optical effects after the rocket launches usually is comparable with auroral light, although at early stages of development it can exceed an auroral light by several times. Thus, it was very convenient to use the large database of all-sky camera optical data to make a long-term study of the peculiarities of the unusual optical effects sometimes seen in the night sky.

The basic data set for our study was obtained at the Loparskaya and Arkhangelsk auroral observatories. These two stations provided the longest and fullest auroral database north of Russia. The list of nine stations, including three Finnish and one Swedish, whose data we used in this study is presented in Table 1. We looked through the data obtained also from other stations, located in Finland (Kilpisjärvi 69.0°N, 20.9°E), northern Russia (Mezen 65.8°N, 44.23°E; Apatity 67.6°N, 33.3°E; and Dixon 73.6°N, 80.57°E) and Southern Spitzbergen (Hornsund 77.0°N, 15.6°E), but Table 1 includes only those stations providing positive results.

We started to look through the data beginning at 1977 and finished with data in 1990. From all of the data, we found 11 cases of unusual optical events that had nothing common with auroral phenomena and obviously had an artificial character. Most interesting for us were events that had been observed from two or three points because it allowed altitudes and sizes of the luminous objects to be estimated. There were six such cases. Table 2 presents the list of events in chronological order. The first case was associated with the launch

Table 1 Observational points

Station	Geographic lattitude	Geographic longitude	Local time (LT) = UT+
Loparskaya	68.62	33.30	+2 h 15 min
Arkhangelsk	64.60	40.50	+2 h 42 min
Sodankylä	67.36	26.63	+1 h 47 min
Muonia	68.03	23.56	+1 h 34 min
Kevo	69.75	27.00	+1 h 48 min
Kiruna	67.83	20.40	+1 h 21 min
Heiss	80.55	58.00	+3 h 52 min
Cheluskin	77.35	104.30	+6 h 57 min
Istok	70.10	88.05	+5 h 52 min

Table 2 Optical atmospheric phenomena observed from two or three points

Date	Time interval, UT	Station	Altitude, km	Size, km
20 Sept. 1977	0104:20–0107:20	Loparskaya	230	~800
	0103–0107	Arkhangelsk		
	0104–0112	Sodankylä		
4 Nov. 1983	0312–0420	Loparskaya	250	~1000
	0312–0320	Sodankylä		
	0313–0316	Kevo		
26 March 1984	2113:20–2118:00	Loparskaya	1080	>1600
	2113–2120	Arkhangelsk		
	2113:20–2116:20	Muonio		
23 Oct. 1985	0120–0130	Loparskaya	1050	>1600
	0123–0132	Kiruna		
25 Dec. 1986	1424–1431	Loparskaya	530	~1200
	1424–1425	Kevo		
23 Dec. 1987	1114–1119	Heiss Island	760	>1600
	1115–1118	Cape Cheluskin		
	1114–1119	Istok		

of the Cosmos-955 satellite. There were no accounts in the press about the launches for the five later cases.

The rarity of optical documentation of these effects can be explained by the specific conditions of sunlight illumination needed for the observations. Specific conditions mean that a scattering object has to be high enough to be illuminated by the sun, whereas an observer has to be in the Earth's shadow, that is, the sun terminator must separate a scattering object and an observer. In the situation when a cloud formation is located inside the Earth's shadow, an observer would see only the flame of vehicle's jet like a moving small bright spot. The weather conditions superimpose more limits on possible observations. Therefore the coincidence of favorable conditions for observations at different stations is quite rare. A detailed description of each event is given later. We tried to make the form of presentation uniform for all cases to make them easier to compare.

We began with the case study on 23 December 1987, the last one in the list of events. This case was chosen for beginning because a most complete set of optical data had been obtained. The set contained both data of television observations at Heiss Island and all-sky camera data from three points (Heiss, Istok, and Cheluskin). These points were located on different sides of the phenomenon at large distances from each other, which make the triangulation measurements more accurate. Photometer observations of the three main auroral emissions were carried out at Istok. On the basis of television data, we were able to obtain dynamic and photometric characteristics, which permitted assumptions to be made on the volumetrical shape of the phenomenon. This case was the first in our study, and the initial results encouraged us to make a historical review of such events based on the great amount of optical all-sky camera data available.

Case Studies

Case of 23 December 1987

Atmospheric optical observations were carried out on Heiss Island, Frantz-Joseph Land (for geographical location, see Table 1) from December 1987 to January 1988 to study dayside auroral phenomena. The main optical instruments were an all-sky camera and a television camera with fish-eye lens. On 23 December 1987, the optical instruments registered an atmospheric phenomenon that obviously had artificial features. The phenomenon was noticed at once on the television screen and represented a bright circular-shaped luminous object, which appeared on the southern horizon at 1114 universal time (UT). Visual observations showed that the luminosity had a light greenish color. The circular luminous object rapidly expanded, and in 5 min reached the zenith of the observational site. Analysis of optical data from another stations in the Russian Arctic region showed that all-sky cameras had registered the same phenomenon in Istok, near Norilsk, and on Cape Cheluskin (see Table 1). All-sky camera pictures taken with a 1-min interval are presented in Fig. 1 and show the development of the optical phenomenon at Heiss Island and Istok. Compass directions are shown in the first image at the left upper corner of Fig. 1. Auroral forms in the southern sector of the sky are seen in the Heiss all-sky pictures superimposing on the image of the luminous object. The distances between these three stations is several hundred kilometers (Heiss–Cheluskin, 960 km; Heiss–Istok, 1380 km; and Cheluskin–Istok, 950 km), and it was the first evidence that the luminosity took place in higher altitudes than auroral ones and covered a vast area. Optical data from three stations provided the possibility to make triangulation analyses to get estimates of the actual size and altitude of the phenomenon.

To determine accuracy and avoid uncertainties and errors in the final results of triangulation measurements on the basis of two-dimensional images one has to know, or at least make corroborated assumptions about, the volumetric shape of the object. For this purpose, we used the dynamic brightness characteristics of the luminous cloud on the basis of the television video data.

We derived the volumetric shape of a luminous object by determining the function of its brightness vs time. Figure 2 was constructed by superposition of three television frames to show sequential positions of the front edge of the luminosity at the times

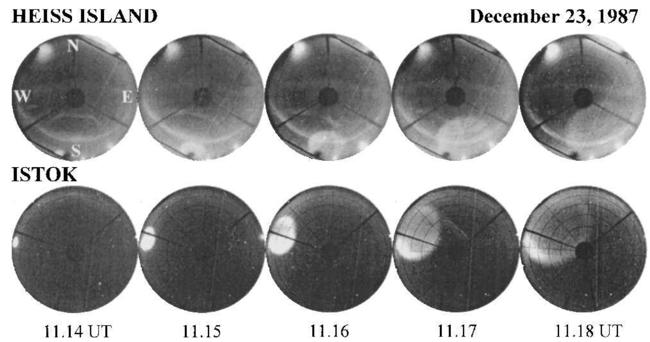

Fig. 1 All-sky camera images of a circular luminous object observed from Heiss Island and Istok.

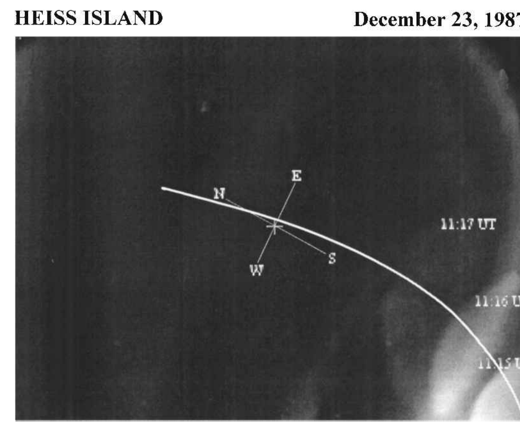

Fig. 2 Superposition of three television frames showing the front of the expanding luminosity at different moments.

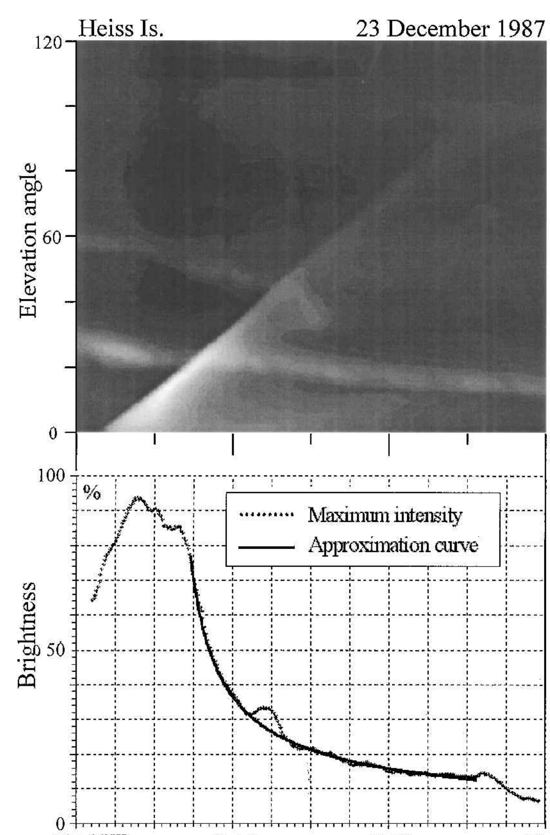

Fig. 3 Dynamic and intensity characteristics of luminous cloud. The upper panel shows development of the luminous cloud presented in the form of spatial–temporal variations along the white line shown in Fig. 2. The vertical axis represents the elevation angle from the horizon. Light bands crossing the brightest one are the auroral light contamination. The lower panel presents a plot of the boundary brightness function vs time and the best-fit interpolation by power approximation.

with 1-min interval (from 1115 to 1118 UT). The television camera field of view was 180 deg along the diagonal of the frame. The white curved line was drawn, always perpendicular to the front edge of the expanding and propagating cloud. Figure 3 (upper panel) presents spatial variations of intensity of the luminous cloud vs time along this line. The intensity variations are almost a straight band, with brightness decreasing in time. The plot of the luminosity brightness maximum vs time is presented in the lower part of Fig. 3.

Analyzing the function, we proceeded from the assumption that the variation of boundary brightness a vs time t under the stable total radiation flux, and different possible volumetric shapes of a luminous object is presented as follows.

Sphere with uniform volume luminosity:

$$a = [A/(t + B)^3] + C$$

1) Sphere with uniform luminosity of surface layer, 2) disk with uniform luminosity, and 3) secondary diffuse scattering by a sphere:

$$a = [A/(t + B)^2] + C$$

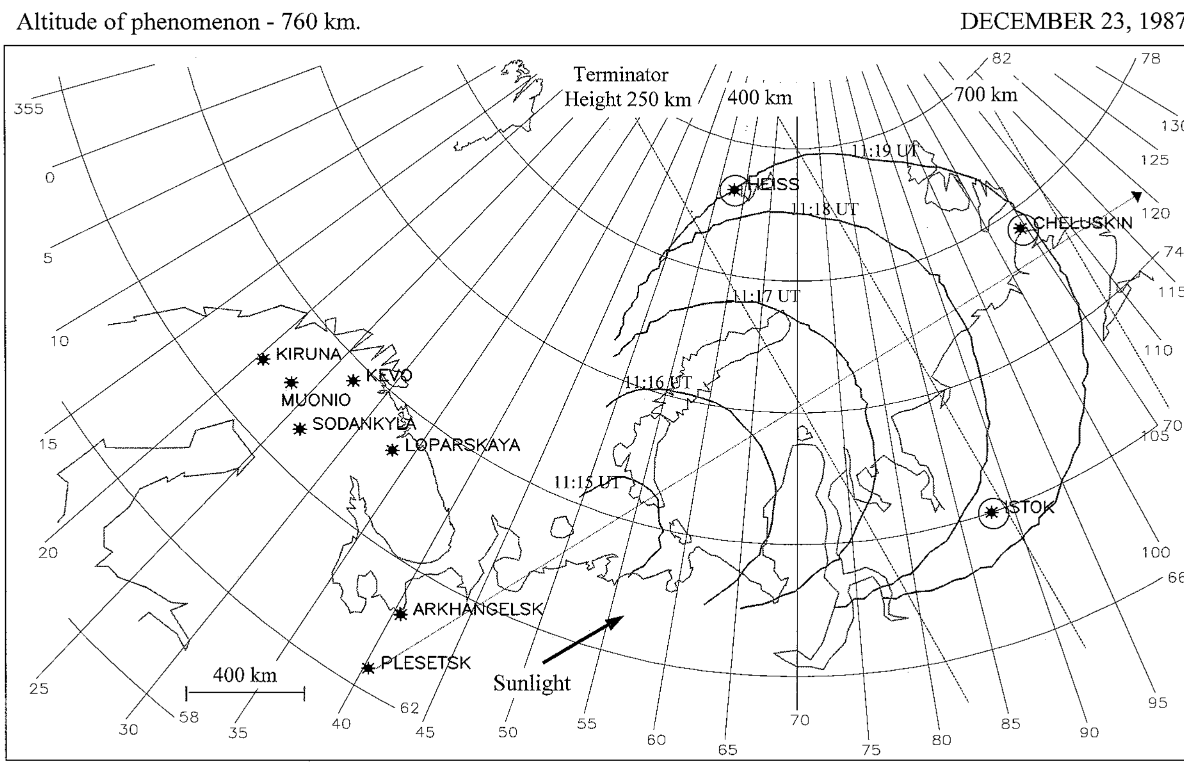

Fig. 4 Results of triangulation mapped on the coastline of northwestern Russia and Scandinavia for case study on 23 Dec. 1987.

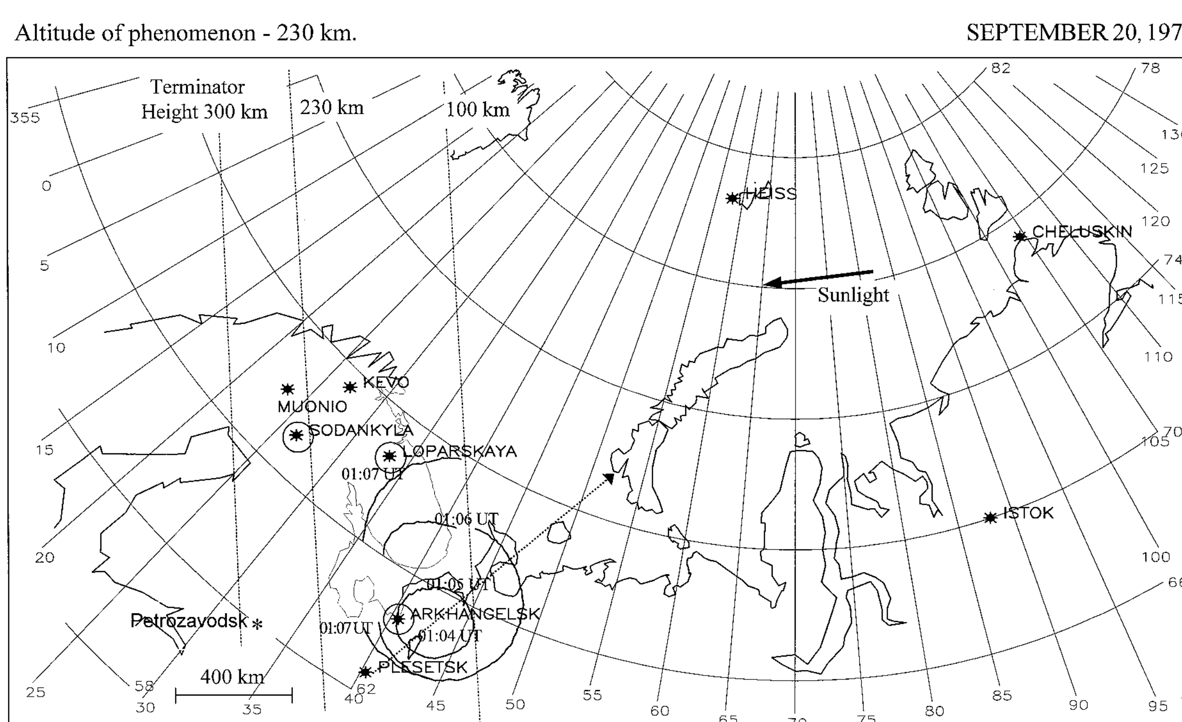

Fig. 5 Results of triangulation mapped on coastline of northwestern Russia and Scandinavia for case study on 20 Sept. 1977.

1) Disk with uniform luminosity at edge (torus), 2) secondary diffuse scattering of a spherical surface, and 3) the secondary diffuse scattering by a disk:

$$a = [A/(t + B)] + C$$

Secondary diffuse scattering of the edge of a disk (diffuse scattering of a torus):

$$a = \left[A \Big/ \sqrt{t + B}\ \right] + C$$

In all expressions, the constants have the following physical meanings: A is the transition coefficient from visual to absolute brightness, B is the transition value to the proper time of the event, and C is the constant background luminosity.

It was determined at the beginning from 1115:30 UT that the best fit was approximated by the function $a = [A/\sqrt{(t + B)}] + C$. Both experimental and approximation functions are shown in Fig. 3 (lower panel). The mean square error of the approximation function is 6.3 times is less than the same parameter of the closest of three other functions. Thus, one might conclude that at the later stages of the cloud development (after 1115:30 UT), the most probable luminosity origin was secondary scattering of a diffuse torus. In the earlier stages, it had a more complicated character.

For triangulation, we used up the all-sky images of the phenomenon from the three stations coinciding in time. Two methods of triangulation were used for this case. The first one was described in detail by Kaila.[27] The method consists of digitizing contours of a luminous object on the pairs of all-sky images made simultaneously at different stations. Each point in the image determines a line in three-dimensional space, which lies through an observational site on the Earth's surface at this point. From the lines going out from each observational site, one can find pairs of closest crossing lines. The middle point between these two lines would be the point sought for in space, determining the altitude and geographical coordinates. The second method of triangulation consists of simple superposition of the images mapped at various altitudes for different stations and finding the best fit of the images, thus obtaining the altitude and dimensions of the object. Results of both methods coincided with an accuracy of about 50 km, in both the horizontal and vertical directions.

The resulting picture of luminous cloud development mapped on the coastline of northwest Russia is shown in Fig. 4. Circular lines represent the shapes of luminosity region determined every minute from 1114 to 1119 UT. The height of luminous region was determined at $\sim$760 km. The horizontal velocity of motion of the center of the circles was about 4.2 km $\cdot$ s^{-1}, the mean velocity of their widening was $\sim$5.6 km $\cdot$ s^{-1}, and the velocity of northeastward propagation of the front edge was $\sim$6.7 km $\cdot$ s^{-1}.

The straight dotted line connecting the centers of the circles comes out from the location of Plesetsk rocket range, which is about 100 km southward from Arkhangelsk. At 1119 UT, when the edge of the luminous circle reached the zenith of Heiss Island, its diameter was approximately 1600 km. The television video data show that the luminosity expanded even for longer time, and its edge crossed the zenith of Heiss Island.

The dashed lines in Fig. 4 show the location of the sun's terminator at different altitudes (for 250, 400, and 700 km). The sunlight was coming from the southwest (thick arrow). The measured altitudes of the luminosity are higher than the terminator at all times during the observations, while the observation points Heiss Island, Istok, and Cheluskin were in deep darkness during this period. (The height of terminator was more than 300 km above all observation points.)

Photometer measurements of the main auroral emissions for the wavelengths λ427.8 nm 1NGN_2^+ (first negative group of molecular nitrogen) and atomic oxygen λ557.7 nm [OI] and λ630.0 nm [OI] were carried out in Istok. Photometers recorded an increase of intensity at about 1118:20 UT. Measurements of the intensity of the emissions showed that they satisfied to Rayleigh's law of sunlight scattering vs λ^{-4}.Thus, it was another confirmation that the luminosity of cloud was caused by the scattering of sunlight.

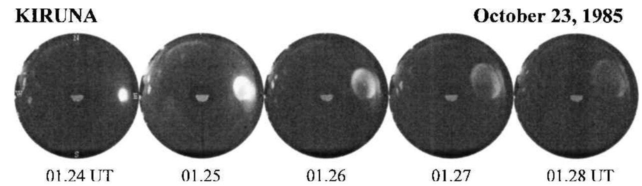

Fig. 6 All-sky camera images of luminous cloud observed at Kiruna on 23 Oct. 1985.

Case of 20 September 1977

This case took place about 10 years earlier than the preceding one (Table 2). A bright luminous cloud attracted the attention of citizens and scientists by its brilliant and spectacular presentation immediately after its appearance in the sky above the city of Petrozavodsk (Karelia, Russia). The phenomenon coincided with an intensive and dynamic auroral display at the same place. That is why later the luminous cloud coinciding with aurora was named the "Petrozavodsk phenomenon." The cloud was registered at three sites: Arkhangelsk, Sodankylä, and Loparskaya (Table 1). Later it was confirmed by a former Soviet newspaper *Pravda*[28] and the journal *Spaceflight*[29] that the phenomenon was caused by the satellite launch Cosmos 955. A brief description of the development of the luminous cloud was given by Platov et al.[16] and Chernouss and Platov.[17]

The results of triangulation carried out for this case are shown in Fig. 5. As in the preceding case, the direction of propagation was northeastward, but the height of luminosity was much lower, at 230 km. The parameters of luminosity motion were as follows: The horizontal velocity of the center of the circles was about 2 km $\cdot$ s^{-1}, the velocity of their widening was about 4 km $\cdot$ s^{-1}, and the velocity of northeastward propagation of the front edge of the luminous cloud was about 3.7 km $\cdot$ s^{-1}. At 0107 UT, the horizontal dimensions of the cloud were approximately 800 km. The dotted lines in Fig. 5 show the location of the terminator for different altitudes at 100, 230, and 300 km. Sunlight was coming from the east (thick arrow).

Case of 23 October 1985

This event was seen from two points: Kiruna (Sweden) and Loparskaya (Russia). The sky above the territory of Finland was overcast. A slight mist was present at Loparskaya, and that is why the all-sky pictures there were made at a 5-min interval. Images of the cloud made at Kiruna are shown in Fig. 6. The results of triangulation are presented in Fig. 7. The altitude of this event was very high, equal to 1050 km. The direction of propagation was again northeastward, and the horizontal velocity of the front edge of expansion was about 3 km $\cdot$ s^{-1}.

The lines with long dashes in Fig. 7 show the location of the terminator for the altitudes of 300, 500, and 1050 km. The sunlight was coming from the east (thick arrow). Although the terminator was very high above the observational points, the luminosity had been even higher. That is why it was clearly seen both in Kiruna and Loparskaya.

Case of 25 December 1986

Two all-sky cameras in Kevo (Finland) and Loparskaya (Russia) registered the luminous cloud. For this case, we obtained an altitude of 530 km (Fig. 8). The direction of propagation is northeastward, but horizontal velocities could hardly be measured; however, rough estimates show that the front edge moved with velocity of about 3 km $\cdot$ s^{-1}.

In this case, the sunlight was coming from the west. The location of the terminator is shown for the altitudes 200, 530, and 700 km. Again, as in the preceding cases, the luminous phenomenon was higher than the Earth's shadow, whereas Loparskaya and Kevo were in darkness.

Case of 4 November 1983

This case is one of two that differ from the preceding ones not only by the height of the luminosity but other characteristics of their presentation. The all-sky images came from three stations: Kevo and Sodankylä (Finland) and Loparskaya (Russia). The launch of a rocket was seen in Loparskaya, first as a white point, which drew a

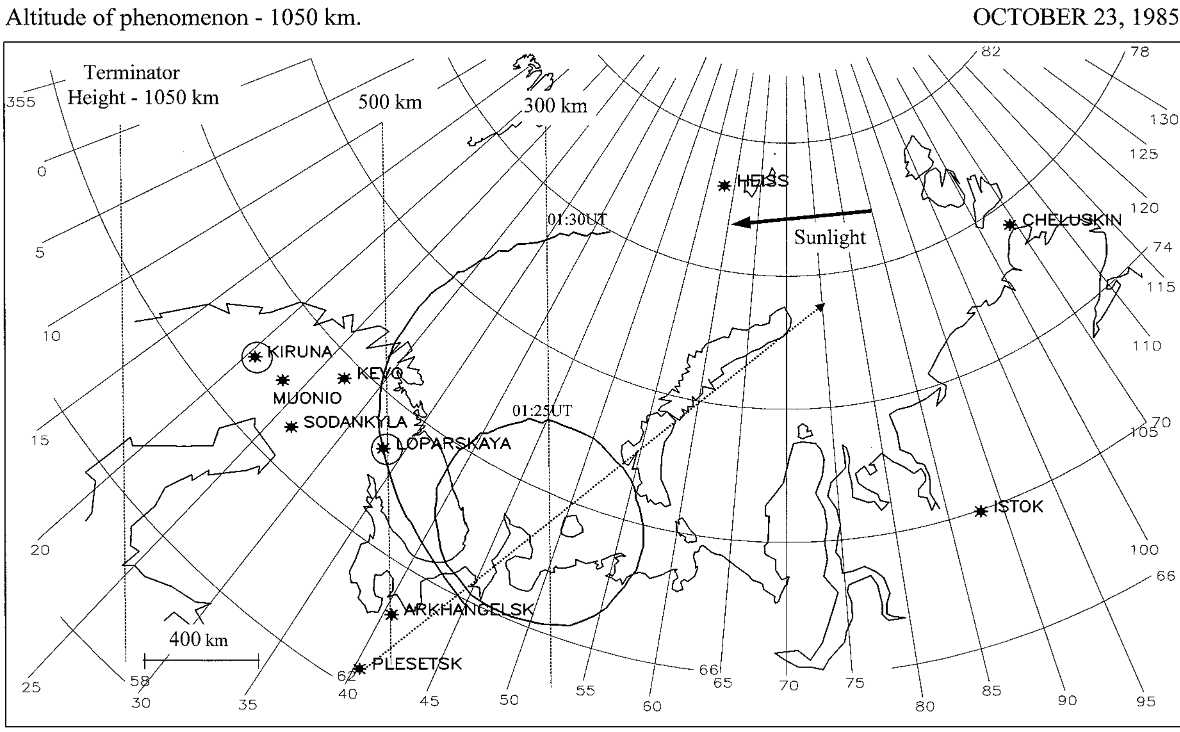

Fig. 7 Results of triangulation mapped on coastline of northwestern Russia and Scandinavia for case study on 23 Oct. 1985.

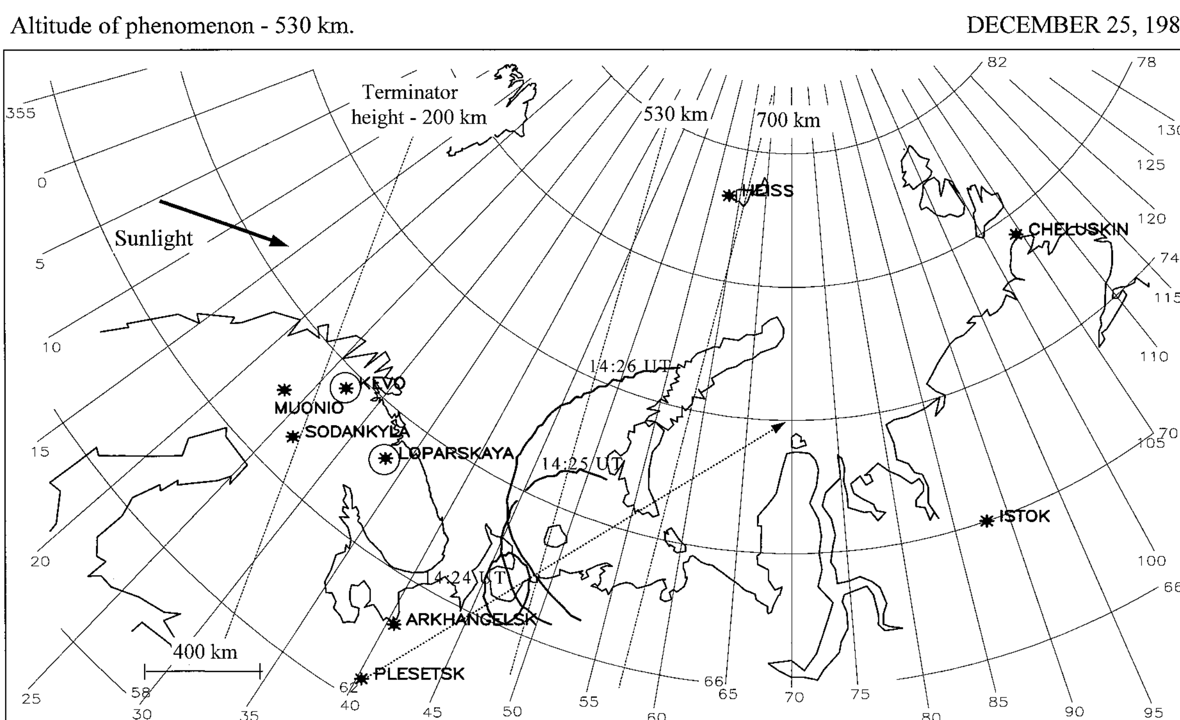

Fig. 8 Results of triangulation mapped on coastline of northwestern Russia and Scandinavia for case study on 25 Dec. 1986.

white dash on the image close to southeastern horizon of image due to exposure time. In 1 min the point transformed to a bright torchlike formation with a sharp pointed head. All three cameras detected the torch. Then the torch developed into a bright luminous colorful cloud that covered more than half of the sky, seen from Loparskaya and Kevo. During further development, a white spot separated from the cloud and a trail stretched out of this spot. The trail was seen for about one hour after the launch, very slowly changing in shape and stretching further southeastward.

We present the results of triangulation measurements in Fig. 9. The results of triangulation show another distinction from the preceding cases. The direction of propagation was northwestward, and the altitude was one of the lowest among the cases (about 250 km). The horizontal velocities of the front edge of the cloud was about 3.5 km $\cdot$ s^{-1}, and the velocity of the center motion was about 2.5 km $\cdot$ s^{-1}. The cloud was close to the terminator, but the trail was entirely illuminated by the sun, especially at later times.

Case of 26 March 1984

This case was observed from three observatories: Loparskaya and Arkhangelsk (Russia) and Muonio (Finland). The results of triangulation are presented in Fig. 10. The altitude of the luminosity was the highest (~1080 km) with regard to all earlier described phenomena. This launch was not made from Plesetsk. The direction of propagation was northward almost along the geographic meridian. The velocity of propagation of the front edge was also highest among all cases and equal to 7.5 km · s^{-1}. Presumably, this case was connected with the launch of a rocket from southern regions of the former U.S.S.R., perhaps from western Kazakhstan. Scandinavia and the Kola peninsula were close to the midnight sector. The sunlight came directly from the north. Therefore, the Earth's shadow was high at the observational points (altitude ~450–500 km).

Other Cases Observed from Single Stations

We briefly point to some other cases, which were registered by standard optical equipment at different places. The list of these cases is given in Table 3. Some of these cases were identified with launches of satellites on the basis of reports of Soviet newspapers. Although we could not make triangulation measurements and find the location of the luminosity, we could estimate that their features had been very similar to those phenomena described earlier. Photometer measurements in different emissions made during the event on 8 January 1986, also showed that the luminosity of the cloud was caused by Rayleigh's scattering of the sunlight.

Discussion

We presented six cases of optical phenomena that were observed from two or three stations and pointed to five more that were registered by a single station. In fact, such phenomena were seen more frequently according to eyewitness accounts.

It was shown that the luminosity effects took place in a much wider altitude range than those that were observed by radio methods. This could be understood because the radio methods could measure effects mainly at the altitude range of the E- and F-regions of the ionosphere where the density of the ionized component is high and radio methods are most effective.

Table 3 Optical atmospheric phenomena observed from a single station

Date	Time interval, UT	Station	Satellite
20 March 1979	1855–~1858	Is.Golomyany[a]	Meteor-2
31 March 1982	0312–0420	Istok	Cosmos-1345
25 Oct. 1985	0403–0409	Kiruna	
8 Jan. 1986	1135–1138	Istok	Cosmos-1715
19 Sept. 1986	2220–2245	Arkhangelsk	

[a]Geographic: latitude 79°N, longitude 93°E.

The burning engines of rocket vehicles are very strong sources of dispersed particles. For example, about 180 tons of particles, mainly aluminum dioxide are generated during the operation of the solid-fuel boosters of the space shuttle. During operation of the liquid-fuel rocket engines, about 30% of the exhaust is condensed with the formation of ice particles. The lifetime of the particles and consequently of the artificial clouds including these particles depends on the precipitation velocity and diffusion in the atmosphere and thermodynamic conditions of the medium where this cloud was generated. The lifetimes of the artificial clouds can vary from several minutes to several hours.[22]

Spatial–temporal and spectral-brightness characteristics of artificially created clouds pointed out in our results and in the literature[19,22] may be explained by the proposal that Rayleigh scattering takes place on the particles, whose radii were estimated to be less than 1μm. These could be particles of a condensate formed as a result of exhaust gas cooling by its rapid expansion due to the great pressure differential between the nozzle exit and the surrounding atmosphere. The existence of such particles can explain the large diametrical dimension of the artificial clouds, that is, the distances on which braking of injected components in the rarefied atmosphere takes place at the altitudes more than 200 km.

All cases presented in our review had common features, although each of them had its own peculiarity. From Table 2, it is seen that the spatial sizes of the cloud formations are geometrically similar, that is, the higher an object was, the larger the area it covered. That is why we used the example of 23 December 1987, the first one in our review, and tried to analyze what in general happens during the period of working engines for rocket launches during the initial part of their trajectory up to about 1100 km.

Gritsai et al.[25] studied the optical effects of stage separation in the launches of multi-stage rockets on the basis of television observations. They found that the artificial cloud formed during booster separation or engine cutoff was more stable than the burning products of fuel before and after separation. The lifetime of the former was 5–10 times longer than that of the latter.

Therefore, the most dramatic events happen during cutoff of the boosters. Noted that at these moments the unused fuel, which always exits the tanks of the rocket, pours out into the atmosphere.

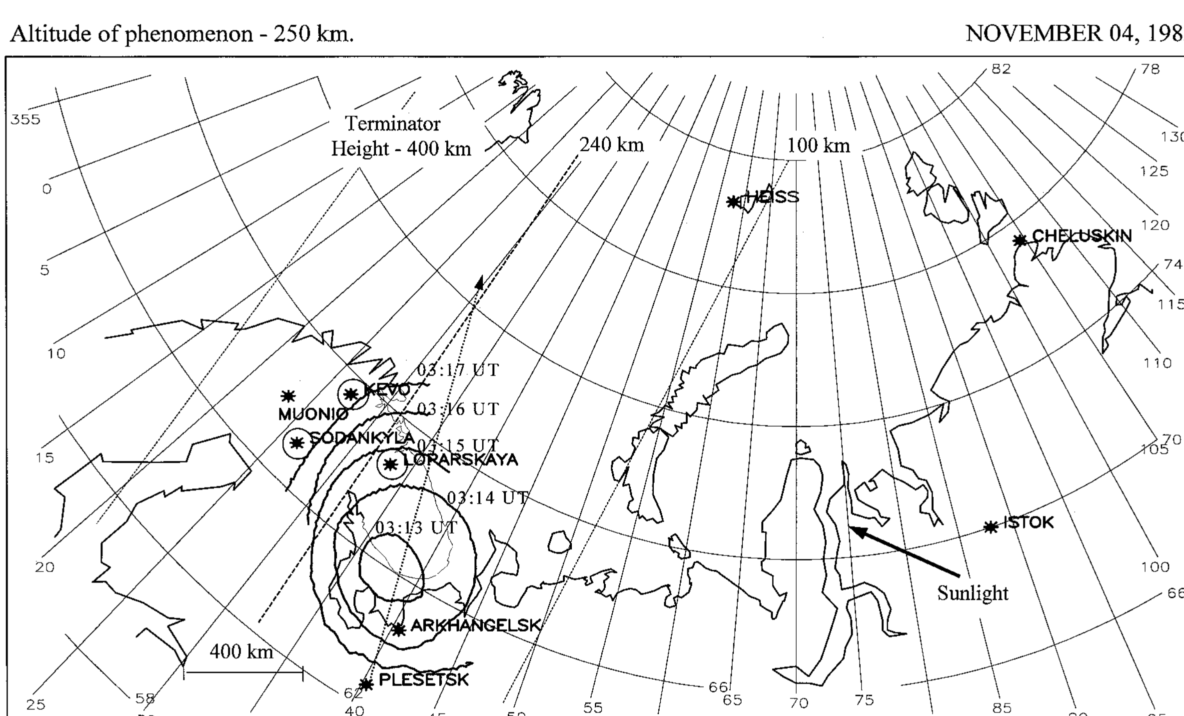

Fig. 9 Results of triangulation mapped on coastline of northwestern Russia and Scandinavia for case study on 4 Nov. 1983.

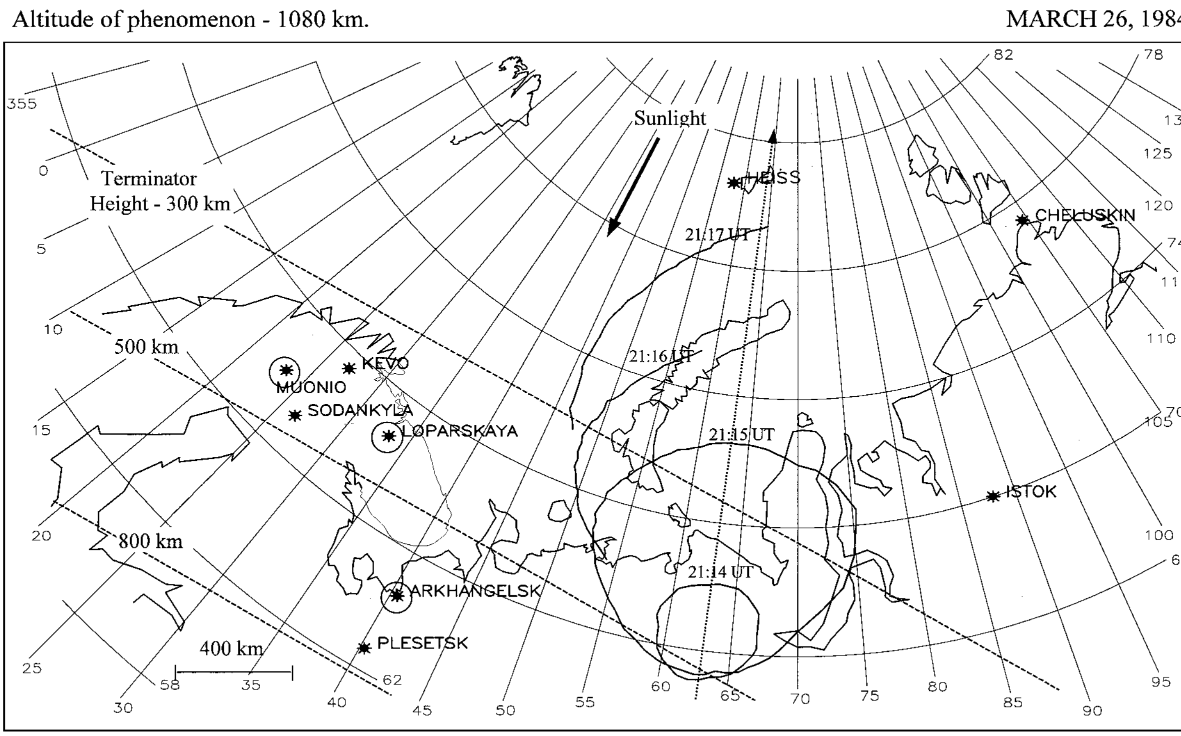

Fig. 10 Results of triangulation mapped on coastline of northwestern Russia and Scandinavia for case study on 26 March 1984.

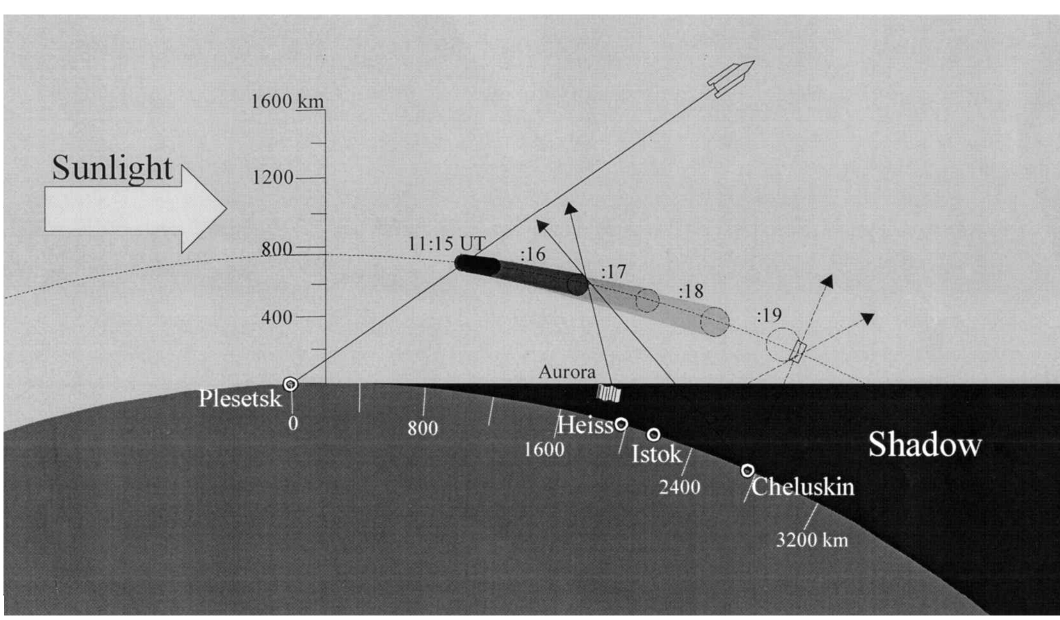

Fig. 11 Probable development of gas and dust cloud after rocket launch on 23 Dec. 1987.

This action does not have a jet character but is a simple ejection of a complicated gas mixture. The ejection usually lasts for a few seconds before other boosters begin to operate or engine cutoff takes place, and a rocket achieves its orbit. Taking this into account, we have to remind ourselves that according to the approximation curve in Fig. 4 the volumetric shape of the cloud formation is more likely to be a torus. This volumetrical shape is also confirmed by the images given in Figs. 1 and 6, where the luminous object looks like a ring with a brighter periphery than its internal part. All of these features suggest that the mechanism of cloud formation is similar to the creation of a smoke ring by a smoker. The atmosphere, the density of which decreases exponentially, is a strong obstacle for dispersed particles to penetrate deeper into the atmosphere. This forces the cloud formation to expand in the horizontal direction, where the atmospheric density is constant. Of course, the components of motion both downward and upward could exist also. The former is due to the weight of the particles, and the latter is a vortex motion due to the friction and viscosity of the atmospheric medium.

The vertical section of the 23 December 1987 case is given in Fig. 11. The section was made along the line of projection of the rocket's trajectory onto the Earth's surface (Fig. 4). The position of the observational points (Heiss, Istok, and Cheluskin) are given as projections onto this line. Figure 11 is in true scales both in the vertical and horizontal directions. Because of the large scale of the phenomenon, we have to take into account the curvature of the Earth's surface.

We suppose that initial vertical size of the cloud was less than 100 km. We proceeded from the assumption that the pouring out of the remaining fuel lasted no longer than 10 s. If the velocity of the rocket was several kilometers per second, then we get a vertical size of about a few tens of kilometers. We also propose that the vertical size of the cloud enlarged during development to approximately twice the initial size.

Bearing these assumptions in mind, it is seen in Fig. 11 that the cloud was entirely above the Earth's shadow up to 1119 UT. At the same time, the auroral structures, which were seen only at Heiss

Island (Fig. 1), were located lower than the sun's terminator, and their position is also shown in Fig. 11.

It is very important to estimate accuracy and possible errors that could arise during triangulation measurements of cloud formations. Two pairs of arrows in Fig. 11 present the crossing lines of sight. In principle, the point of crossing determines the altitude and horizontal coordinates of one of the points of the object. It is seen that this point could be lower or higher than the mean altitude of the cloud formation, which in the present case was 760 km. The possible dispersion of this point lies in a rectangle, the sides of which are estimated in the vertical direction to be ~10–12% of altitude and ~5–7% of the horizontal dimensions. Thus, the spatial characteristics given in Table 2 are mean values of the heights and diametrical sizes with the accuracy, which gives an estimation of the thickness of a cloud.

Conclusions

The results of ground-based optical observations of luminous clouds caused by launches of powered rockets point to the following peculiarities.

1) The altitudes of the luminous clouds varied in the range from 230 to 1080 km, but the clouds could be observed only under specific sunlight conditions when they occurred above the sun's terminator and an observation point was located deep inside the Earth's shadow. The altitude of the phenomena did not change in the estimated accuracy range of 10–12% of the measured altitude.

2) The luminosity of the clouds was caused by Rayleigh scattering of sunlight on dispersed particles existing in the gas and dust clouds produced by a rocket, mainly at the moments of booster separation or engine cutoff.

3) The luminous clouds represent rapid horizontally expanding formations with a prevailing direction of propagation along the trajectory of the rocket. The mean values of the horizontal velocities of the front edges of the luminous clouds varied from 3 to 5 $km \cdot s^{-1}$. The maximum velocity was measured for one of the highest cases (26 March 1984) and was equal to 7.5 $km \cdot s^{-1}$.

4) All clouds were topologically similar, which means the higher the clouds were the larger were their final geometrical dimensions. The maximum visible horizontal dimensions at the later stages of cloud development were more than 1600 km. It is most probable that the clouds had a toruslike spatial form. This assumption was confirmed both by television data analysis and the images of individual cases. The maximum value of the vertical extent is estimated to be about 200–250 km.

5) The lifetime of the visual objects registered by standard all-sky cameras varied from several minutes to several tens of minutes. Sometimes a longer lasting luminous trail could be seen after the disappearance of the main cloud.

6) All of the described features of the effects caused by rocket launches show that they can cover vast territories at very high altitudes. Sometimes they can be registered only by optical equipment, which can be standard cameras for routine all-sky observations, and these data can provide very important information on the influence of the rocket launches on the surrounding space environment.

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