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OPTICAL PHENOMENON IN THE ATMOSPHERE CAUSED BY POWERED ROCKET LAUNCHES

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Abstract. We present the results of observations of optical effect in the atmosphere, which was observed at first at Heiss Island (Frants-Joseph Land) on 23 December 1987 by means of all-sky TV camera. Further analysis of optical data from other stations allowed to find the signatures of this phenomenon at Cape Cheluskin and Norilsk. The analysis of TV data allowed to make assumptions on volumetrical shape of the phenomenon. Results of triangulation measurements showed that the height of it was about 760 km above the Earth surface. Further analysis showed that the phenomenon was caused by launch of powered rocket from Plesetsk rocket range.

Results of observations

Atmospheric optical observations were carried out at Heiss Island, Frants-Joseph Land, (geographical location see in Table 1) in the period of December 1987-January 1988, to study dayside auroral phenomena. The main optical instruments at that moment were all-sky camera and TV camera with fish-eye lens. On 23 December 1987, the optical instruments registered an atmospheric phenomenon, which obviously had artificial features. It was noticed at once on the TV screen and it represented a bright circular shaped luminous object, which appeared at southern horizon at 11.14 UT. Visual observations showed that the luminosity had light greenish color. It rapidly expanded and in five minutes reached the zenith of observational site. Analysis of optical data from other stations in the Russian Arctic region showed that all-sky cameras had registered the same phenomenon at Istok, near Norilsk, and at Cape Cheluskin (see Table 1). All-sky camera pictures taken with 1-minute interval presented in Fig.1 show development of the optical phenomenon at Heiss Island and Istok. In the images North was in upward direction and West was at the right side. Auroral forms at southern sector of the sky are seen in Heiss all-sky pictures superimposing on the image of the luminous object. The distances between these three stations are about several hundreds kilometers (Heiss-Cheluskin - 960 km; Heiss-Istok - 1380 km; Cheluskin-Istok - 950 km) and it was the first evidence that the luminosity region took place in higher altitudes than auroral ones and covered vast area. Optical data from three stations provided possibility for making triangulation analysis to get estimations of actual size and altitude of the phenomenon.

Table 1. List of observational points

Station	Geogr. latitude	Geog. longit.	Time LT=UT+
Heiss	80.55	58.00	+3h 52m
Cheluskin	77.35	104.3	+6h 57m
Istok	70.10	88.05	+5h 52m

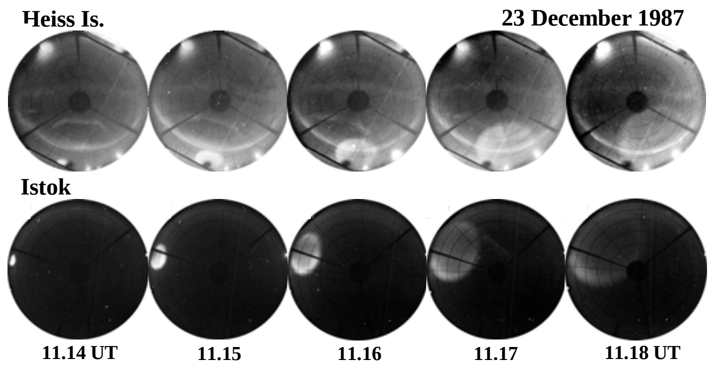

Fig.1. All-sky camera images of circular luminous object observed from Heiss Island and Istok. Auroral arcs are also seen in the images of Heiss Island. North is upward and East is at the right side.

Before making triangulation measurements on the basis of 2-dimensional pictures one has to know or at least to make corroborated assumptions about volumetrical shape of the object in order to determine accuracy and avoid uncertainties and errors in the final results. For this purpose we used its dynamic brightness characteristics of the luminous cloud on the basis of TV video data. We derived the voluментary shape of luminous object as a function of its brightness versus time. Fig. 2 was constructed by superposition of three TV frames to show sequential positions of front edge of luminosity at different moments with 1-minute interval (11.15 - 11.18 UT). The white curved line was drawn always perpendicular to front edge of the expanding and propagating cloud. Fig.3 (upper picture) presents spatial variations of intensity of the luminous cloud versus time along this line. The variations represent almost straight band with brightness decreasing in time. The light bands crossing the former one represent auroral motion along the same white line at the same interval. The plot of brightness versus time is presented in Fig. (lower picture).

Analyzing the function we proceeded from the assumption that variation of boundary brightness *a*, versus time *t* on the conditions of stable total radiation flux and different possible volumentary shapes of luminous object are presented as follows:

$$a = \frac{A}{(t+B)^3} + C$$ - sphere with uniform volume luminosity;

$$a = \frac{A}{(t+B)^2} + C$$ - (1) sphere with uniform luminosity of surface layer; (2) disk with uniform luminosity; (3) secondary diffuse scattering of a sphere;

$$a = \frac{A}{t+B} + C$$ - (1) disk with uniform luminosity of edge (torus), (2) secondary diffuse scattering of spherical surface; (3) secondary diffuse scattering of a disk;

$$a = \frac{A}{\sqrt{t+B}} + C$$ - secondary diffuse scattering of edge of a disk (diffuse scattering of a torus), where constants have the following physical values: A is transition coefficient from visual to absolute brightness; B is transition coefficient to the proper time of the event; C is coefficient of constant background luminosity contamination.

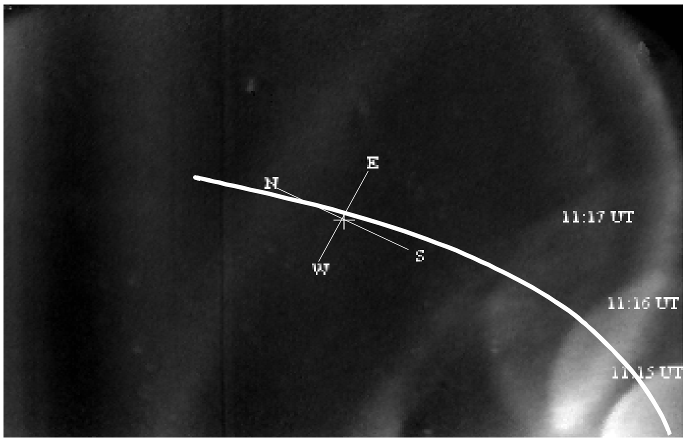

Fig.2. Superposition of three TV frames showing the front of expanding luminosity at different moments. The white line is drawn approximately perpendicular to the front edge of luminous cloud. The field of view of TV camera was 180° along the diagonal of the frame.

It was determined that beginning from 11:15:30 UT the best fit had approximation by function $a = \frac{A}{\sqrt{t+B}} + C$. Both experimental and approximation functions are shown in Fig.3 (lower picture). Mean square error of the approximation function is 6.3 times less than the same parameter of closest function at different parameters A, B and C. So one might conclude, that at the later stages of the cloud development after 11:15:30 UT, the most probable luminosity origin was secondary scattering of diffuse torus or something similar to it. At earlier stages it had more complicated character.

For triangulation we had picked up the all-sky images of the phenomenon from three stations coinciding in time. We used triangulation method proposed by *Kaila* [1987] for auroral forms altitude measurements.

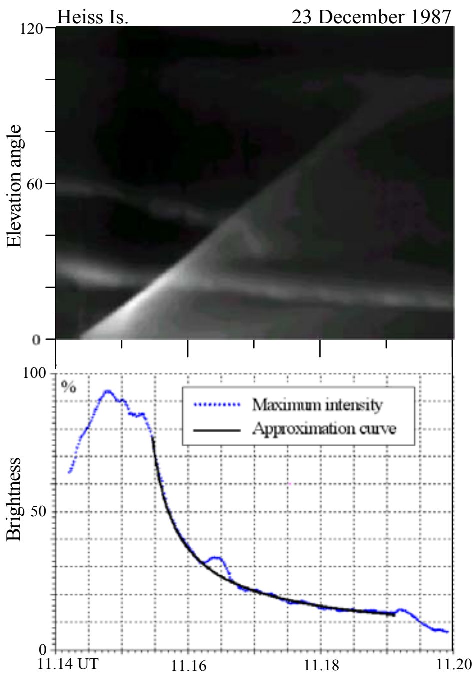

Fig.3. Upper part - development of luminous cloud presented in the form of spatial-temporal variations along the white line, shown in Fig. 2. Lower part - plot of the edge brightness function versus time and the best-fit interpolation by power approximation.

The resulting picture of luminous cloud development mapped on the coastline of North-Western Russia is shown in Fig.4. Circular lines represent the shapes of luminosity region determined every minute from 11.14 to 11.19 UT. The heights of luminosity region was determined ~ 760 km. The horizontal velocity of motion of center of the circles was about 4.2 km/s, the mean velocity of their widening was ~ 5.6 km/s whereas velocity of northeastern propagation of the front edge was about 6.7 km/s.

The straight dotted line, which connects the centers of the circles comes out from location of Plesetsk rocket range, which is about 100 km southward from Arkhangelsk. At 11.19 UT, when the edge of luminous circle reached the zenith of Heiss Island its diameter was approximately 1600 km. The TV data show that the luminosity expanded even longer and its edge crossed the zenith of Heiss Island.

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

Photometer measurements of the main auroral emissions on the wavelengths λ427.8 nm $1NGN_2^+$, λ557.7 nm [OI] and λ630.0 nm [OI] were carried out at Istok. Photometers registered an increase of intensity at about 11:18:20 UT. Measurements of the intensity of the emissions showed that they satisfied the Rayleigh's law of the sunlight scattering λ^4. So it was another confirmation, that the luminosity of cloud was caused by scattering of sunlight.

Discussion

The burning vehicles of rocket-careers are very strong source of dispersed particles. For example, about 180 tons of particles, mainly aluminum dioxide are generated during the operation of hard-fuel boosters of Space Shuttle. During the operation of liquid-fuel rocket engines about 30% of exhaust is condensed with formation of ice particles. Lifetime of the particles and consequently of artificial clouds including these particles depends on precipitation velocity and diffusion in the atmosphere, thermodynamic conditions of the medium, where this cloud was generated. It can vary from several minutes to several hours [*Rote,* 1980; *Vetchinkin,* 1993].

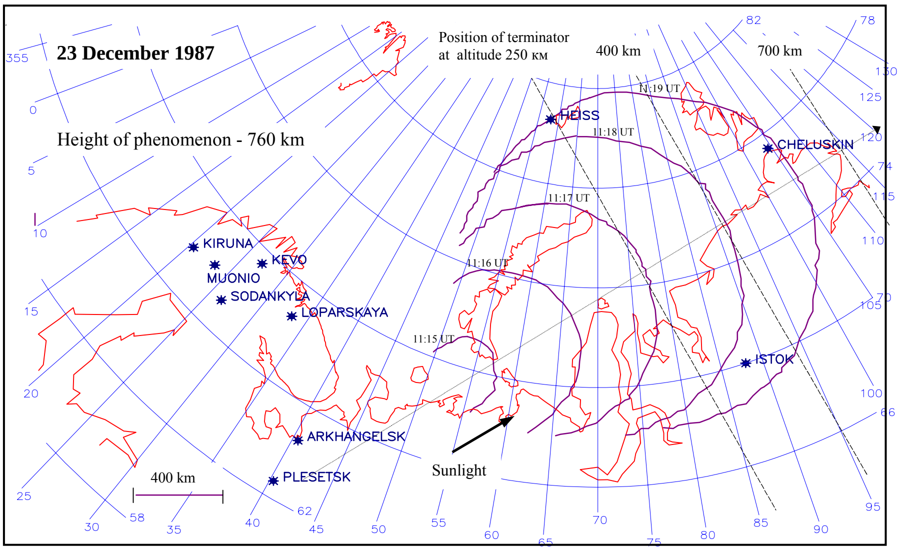

Fig.4. Results of triangulation mapped on the coastline of northwest of Russia and Scandinavia for case on December 23, 1987. The circular lines show the edges of luminosity objects at different moments, dotted line indicates the direction of luminosity propagation, dashed lines show the position of Sun terminator at different altitudes.

Spatial-temporal and spectral-brightness characteristics of artificially created clouds shown in our results and in literature [*Vetchinkin,* 1993; *Klimenko,* 1995] may be explained by suggestion that the Rayleigh's scattering takes place on the particles, thier radius was estimated to be less than 1 mkm. Those could be particles of a condensate, formed as the result of exhaust gas cooling by its rapid expansion due to great pressure difference between the nozzle exit section and the surrounding atmosphere. The existence of such particles can explain large diametrical dimension of artificial clouds, i.e., the distances at which braking of injected components in the rarefied atmosphere takes place at the altitudes more than 200 km.

Gritsai et al. [1996] studied optical effects of stage separation in the launches of multi-stage rockets on the basis of TV observations. They found out that artificial cloud formed during booster separation or engine cut-off had been more stable than the burning products of fuel before and after separation. The lifetime of the first was 5-10 times longer than the second one.

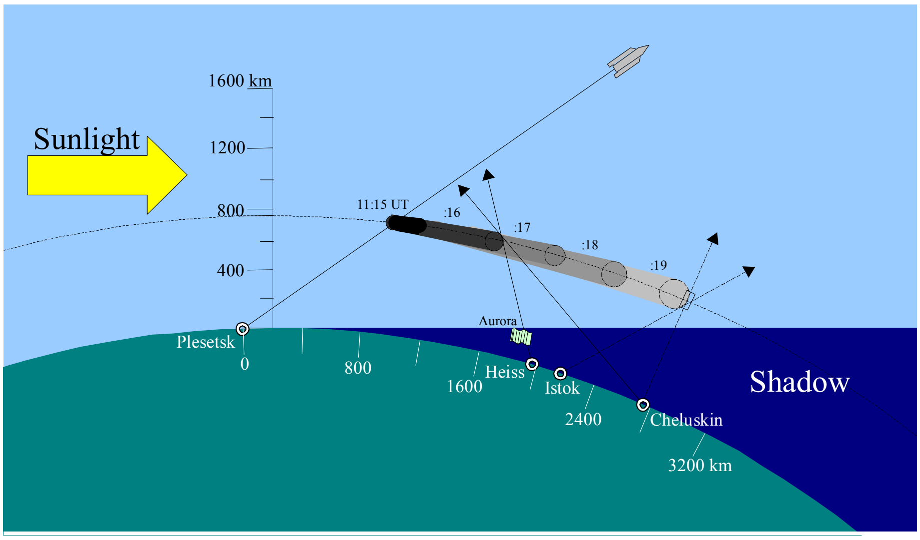

Fig.5. Sketch showing probable development of gas-and-dust cloud after the launch of rocket on December 23, 1987. Pairs of arrows indicate the crossing rays of sight from different stations. The rectangle represents possible error in estimation of real sizes and height of the cloud.

So the most drastic events happen during cut-off of the boosters. It should be noted that at these moments the unused rest fuel, which always exist in tanks of rocket pours out into the atmosphere. This action is not of the jet nature, but simply presents throwing out of complicated gas mixture. It lasts usually for a few seconds before another boosters begin to operate or engine cut-off takes place and the rocket reaches its orbit. Taking this into account we have to remind that according to approximation curve in Fig.3 the volumentary shape of the cloud formation more likely looks like torus. This is confirmed also by the images given in Fig.1, where the luminous object looks like a ring with more brighter periphery than its internal part. All these features allow to propose that the mechanism of cloud formation is similar a smoke ring exhausted by a smoker. The atmosphere, the density of which grows downward exponentially is a strong obstacle for dispersed particles to penetrate deeper into the atmosphere. This forces the cloud formation to expand in horizontal direction, where the atmospheric density is constant. Of course, components of motion both downward and upward also exist. The former is due to weight of the particles and the latter is a vortex motion due to friction and viscosity of atmospheric medium.

We had drawn a sketch of vertical section of the case on December 23, 1987, which is given in Fig.5. The section was made along the line of projection of rocket's trajectory to the Earth' surface (Fig.4). Position of the observational points (Heiss, Istok and Cheluskin) are given as projections to this line. Sketch is drawn in true scales both in vertical and horizontal directions. Because of large scales 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 suggestion that pouring out of the rest fuel lasted not longer than 10 sec. If the velocity of the rocket was several km/s, then we get vertical size about few tens of km. We also propose that vertical size of the cloud enlarged during the development approximately twice.

According to these assumptions it is seen in Fig.5 that the cloud was entirely above the Earth's shadow up to 11:19 UT. At the same time, the auroral structures, that were seen only from Heiss Island (Fig.1) were located lower the Sun terminator and there position is also shown in Fig.5.

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

Conclusions

The results of ground based optical observations of luminous cloud, caused by launch of powered rocket, indicate the following peculiarities:

1. Altitude of luminous cloud was 760 km, but it could be observed in specific sunlight conditions when it occurred above the sun terminator and an observation point was located deep inside the Earth's shadow. The altitude of phenomena did not change in the estimated accuracy range 10-12% of measured altitude.

2. Luminosity of the cloud was caused by Rayleigh's scattering of sunlight on the dispersed particles, existed in the gas and dust clouds produced by the rocket mainly at moments of booster separation or engines cut-off.

3. Luminous cloud represented rapid horizontally expanding formation with prevailing direction of propagation along trajectory of the rocket. The value of horizontal velocities of front edge of the luminous cloud was 6.7 km/s.

4. Maximum visible horizontal dimensions at the later stages of cloud development were more than 1600 km. It is most probable that clouds had torus-like spatial form, that is confirmed both by TV data analysis and the images of individual cases. The vertical extent was proposed to be about 100 km.

All described features of the effect caused by rocket launch show that it covered vast territory at very high altitudes. It could be registered only by optical equipment, which had been standard cameras for routine all-sky observations and low-light level TV camera. This data provides very important information on influence of the rocket launches on the surrounding space environment.

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