"Physics of Auroral Phenomena", Proc. XXV Annual Seminar, Apatity, pp.103-106, 2002

Polar Geophysical Institute

CLASSIFICATION OF GAS-DUST FORMATIONS FROM ROCKET EXHAUST IN THE UPPER ATMOSPHERE BY SCALE AND DYNAMICS

Yu. Platov(1), S. Chernouss (2), and G. Kulikova (1)

(1) Institute of Terrestrial Magnetism, Ionosphere and Radiowave Propagation of RAS, Troitsk, Moscow Region.
(2) Polar Geophysical Institute of RAS, Apatity, Murmansk Region.

Introduction

The launches of powerful rockets and output of space vehicle engines are accompanied by the injection of combustion products with a complex structure into the atmosphere. These products contain both gas and dispersed solid components that result in the development of gas and dust clouds having certain geometric and dynamic features. The development of such artificial formations in the upper atmosphere is accompanied by rather unusual optical phenomena caused by the scattering of sunlight from the combustion products as well as their interaction with constituents of the upper atmosphere [1 - 5]. Investigations of these optical phenomena permits studies of anthropogenous pollution of near-Earth space, interaction processes of the pollution with the environment and dynamic processes in the upper atmosphere.

The optical signatures in the upper atmosphere accompanying rocket launches made from the Plesetsk cosmodrome and White Sea rocket ranges have been registered for many years by all-sky cameras in the northern regions of the former Soviet Union as part of normal auroral recordings. Over fifty rocket plumes and large-scale diffusive formations have been captured on photographic film.

The investigations of dynamical and structural parameters are the most interesting large-scale artificial formations in the upper atmosphere were carried out by different authors. In particular, it was shown, that characteristic velocity of expansion of a gas-dust clouds formed by rocket exhausts is 1-2 km/sec, and their size can reach several hundreds kilometers in diameter. Interaction of a gas phase of combustion products with the atmosphere components results in the change of speeds and directions of ionic - molecular reactions which can result in occurrence of anomalies in the own luminescence of the upper atmosphere [6-9]. The analysis of optical recordings allows a general estimation of the

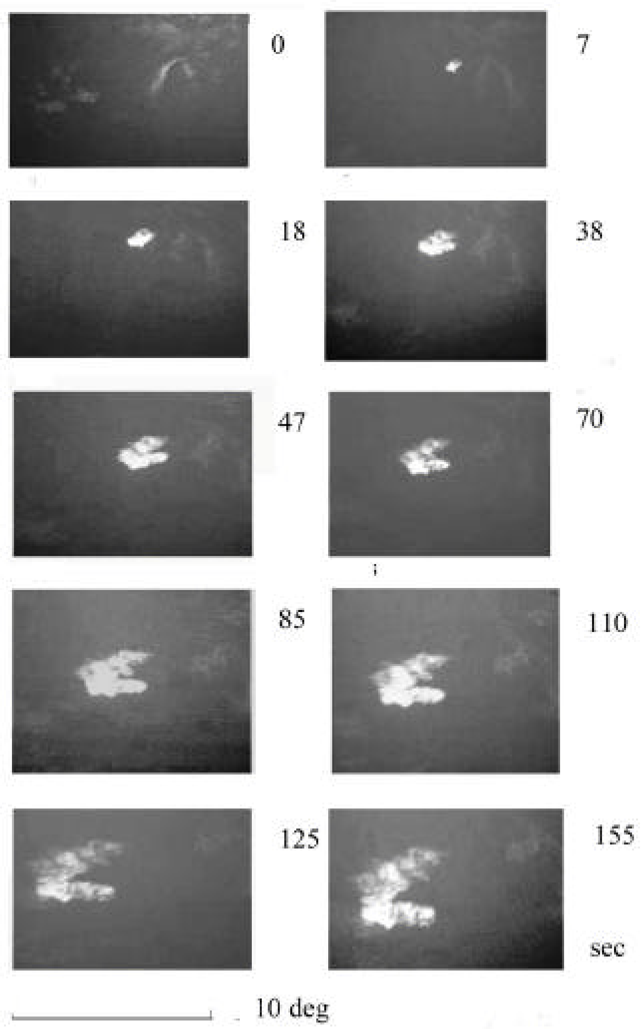

Fig. 1: Development of the cloud formed as a result of the release of excess fuel after separation of the first stage of a liquid fuel rocket at about 45 km altitude. The cloud formation is about 250 km from the point of observation. The angular scale is given along with elapsed time in seconds after initial discovery of the luminous cloud.

lifetime of the phenomena as well as conclusions as to the physical mechanisms involved.

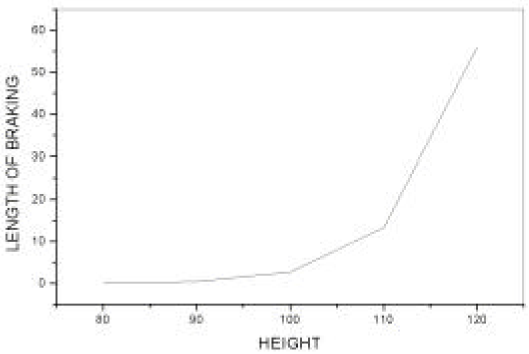

Fig. 2: The characteristic braking distance of 1 micron ice particles with altitude.

Analysis and Discussion

In general, it is possible to divide the large-scale observations into several basic types:

1) Stratospheric phenomena at a height of 40-50 km: These phenomena are connected with the discharge of excess fuel components after separation of the launcher's first stage and the exhaust of the brake engines of the separated stages. The main features of stratospheric formations are: (a) rather a small expansion speed determined by diffusion and wind spreading of the combustion products; (b) long lifetimes; and (c) rather a high brightness, which permits ground-based observations of the formations both during twilight and daytime conditions. These features are basically determined by the physical conditions prevailing in the stratosphere but also by the nature and amount of exhaust products injected into the atmosphere. Fig. 1 is a sequence of images showing the development of an artificial cloud formed by the exhaust of brake engines from the separated first stage of the rocket . The total mass of exhaust material is estimated to be 500 kg injected at approximately 45 km. Clearly, a certain degree of environmental pollution is taking place.

2) Turbopause phenomena at the height of 100-120 km: These phenomena are observed during twilight and are determined by the scattering of sunlight from an extended cloud of combustion products. They have rather a high brightness and are frequently observed visually from distances up to 1000 km. The expansion speed of such formations is about 1-2 km/sec with a characteristic cross-sectional size of 100-200 km. The localisation of these phenomena to 100-120 km altitude is determined by the braking of the dispersed solid components of combustion products in the upper atmosphere. The loss of momentum for a large particle moving in the upper atmosphere is described by $m\,dt = p r^2 V^2 r\,dt$, where $m = 4/3\,p r^3 r_o$ is the mass of a particle, r_o is the particle density, r its radius, V its velocity, and r the atmospheric density. The particle's change in velocity is given by $V = V_o /(1 + 3r\,V_o\,t / 4r_o r)$, and its characteristic braking distance, i.e. the e-folding distance, is given by $L = 4r_o r / 3r\,\ln(1 + t/t)$ where $t = 4r_o r / 3r\,V_o$. Fig.2 shows the variation in braking distance with altitude for 1micron size particles for the model atmosphere in [10].

At altitudes below 100 km, the rocket exhaust trail retains a small cross-sectional size and so remains optically bright. At altitudes above 120 km, the dispersed solid particles expand freely and therefore the exhaust trail is not as optically bright. The intensity of sunlight scattered from the gaseous component of the combustion products is small in comparison to scattering from the dispersed solid particles of the exhaust trail. Fig. 3 shows the development of the gas and dust cloud at 100-130 km formed during the launch of a „Molniya" satellite. The scattering of sunlight from rocket exhaust trails is also evident in the upper atmosphere, however, the fast expansion of the combustion products and the low power of final stage rocket engines results in reduced optical intensities by several orders of magnitude [1, 3].

3) Large-scale dynamic phenomena at 150 km or higher: These phenomena are connected to special modes of rocket engine operation, in particular, shut off of solid fuel rocket engines. This process is connected with a sudden drop in pressure in the combustion chamber that results in practically instant injection of large quantities of fuel components and incomplete combustion products into the atmosphere. Several hundreds of kilograms of material are released as a dispersed dust cloud. The mass of matter injected into the atmosphere is a function of the combustion chamber pressure, volume and temperature: $M = mPV / RT$, where P is pressure, V is volume, T is temperature and μ is the average molar weight of the exhaust products. For typical values of P = 10 Mpa, V = 20 m^3, T = 2800 K, and μ = 0.035 [11], the mass released is ~ 300 kg. In exceptional cases, such artifical clouds may rise up to 700 km, their cross-sectional size may exceed 1500 km [5] with an expansion rate of 2-3 km/sec. The lifetime of such formations is determined by the time taken for the various components to precipitate under gravity down to about 100 km altitude, i.e. the turbopause boundary. These rocket trails have been widely observed not only in Russia but around the World during power solid fuel rocket launches. Fig. 4 shows an example of a high altitude rocket plume taken with an all-sky camera. It is interesting to note that the unique nature of these formations with no comparable natural phenomenon, their large size, and the opportunity to observe them from long distances across political boundaries, often resulted in sensational reporting in the mass media of unidentified flying objects (UFO) [12, 13].

It seems obvious that the dynamic and morphological features of the artificial clouds are a function of the relative quantities of gaseous and dispersed solid components from the rocket exhaust. The characteristics of two basic types of optical phenomena resulting from rocket launches through the upper atmosphere are given below:

A) Long lifetime luminous formations:

Height of artificial cloud: 100-120 km. Characteristic size: ~100 km.

Formation lifetime: 0.1-6 hours or more.

Type of spectrum: discrete lines and molecular bands.

Brightness: up to 10^{-6} sb.

Cloud structure: molecular gas components of rocket exhaust.

Luminosity mechanism: Mostly resonant scattering of sunlight on combustion products interacting with atmospheric constituents.

Dynamic development of the cloud: molecular diffussion [14].

B) Short lifetime luminous formations:

Height of artificial cloud: 100-700 km. Characteristic size: 100-1000 km.

Formation lifetime: 1-10 minutes.

Type of spectrum: continuous emission.

Brightness: up to 10^4 sb.

Cloud structure: dispersed solid particles from the rocket exhaust with 0.1-10 micron characteristic sizes.

Luminosity mechanism: scattering of sunlight by dispersed particles.

Dynamic development of the cloud: spreading of dust cloud.

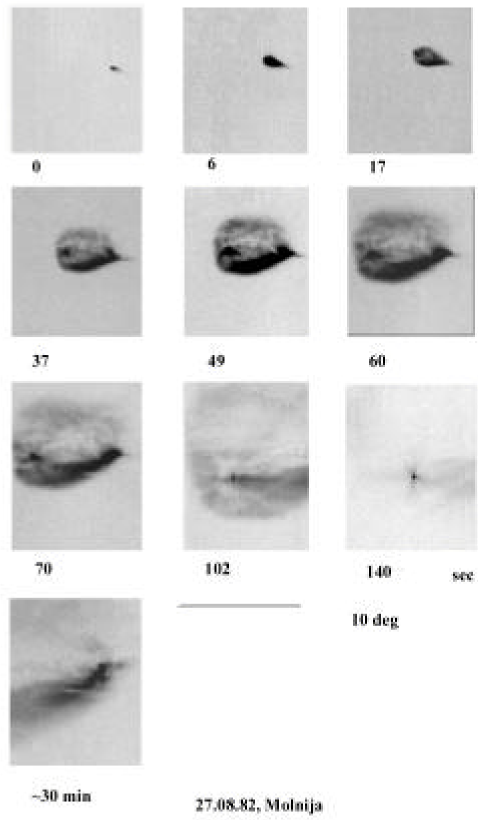

Fig. 3: Negative images of the development of the gas and dust cloud of rocket exhaust from the launch of the „Molniya“ satellite from Plesetck. The cloud formation is about 500 km away from the point of observation. The angular scale is given along with elapsed time in seconds after initial discovery of the luminous cloud. In the 9th frame (140 sec), only the rocket plume is visible and the cloud of combustion products remains undetected. At this time, the rocket altitude is more than 160 km. The last frame shows the glow from the artificial cloud above the turbopause.

The last type of phenomena connects with solid fuel rocket launches exclusively because the dust long-lived particle (Al, Al_2O_3) are contained in its exhausts only. The dispersed ice particles from the rocket exhaust, with sizes up to several microns, are formed as the result of water vapor condensation due to the rapid expansion of the combustion [1, 15, 16]. These authors show that the observed luminosity can be explained by a 5-10% of the water vapour condensing into ice crystals with a typical size of ~100 Angstrom. This mechanism appears to hold for both liquid and solid fuel rockets. Such artificial clouds not only explain the presence of luminous rocket trails but also other observations in the upper atmosphere, for example, the formation of ionospheric electron density holes due to chemical interactions with the combustion products. The spreading of the ice crystals after formation provides rapid transport of a catalyst for the observed phenomena. Furthermore, sublimation of the ice during the spreading process increases the possibility physical and chemical interactions. Detailled consideration of the condensation-transfer-sublimation process will be presented in a future manuscript.

The observations clearly show that both mechanisms of luminosity production (scattering and chemical interactions) are operating. For example, Fig. 4 shows that after the initial dynamic phase of the artificial cloud formation rather a weak diffuse luminosity remains for a long time (several hours until sunrise stopped observations) at the location where a rocket stage separation took place.

References

1.*Kung R.T.V,.Cianciolo and L,MyerJ.A.* Solar Scattering from Condensation in Apollo Translunar Injection Plume //*AIAA Journal.*, 1975. V.13. No.4, P. 432-437

2.*Platov Ju.V., Feshin B.A., Chernouss S.A.* The abnormal phenomena the facts and fiction//the Science in the USSR (Nauka v SSSR, Russia). 1989. No. 5, P. 14-22.

3.*Chemouss S. A., Platov Ju. V.* Optical Effects of Exhaust Products of a Rocket Launches, // " *Proceedings of the 19th European Meeting on Atmospheric Studies by Optical Methods*, edited by A. Steen, IRF Scientific Rept. 209, Swedish Inst. of Space Physics, Kiruna, Sweden. 1992. P. 501-505.

4.*Vetchinkin N.V., Granitskij L.V., Platov Ju.V., Shejhet A.I.* The optical phenomena in the circumterraneous environment at work of impellent installations of rockets and satellites. I. Ground and satellite supervision of artificial formations(educations) at start of rockets//Space researches (Kosmicheskie issledovanija, Russia). 1993. V.31. No. 1, P. 93-100.

5.*Tagirov, V. R., Arinin, V. A., Brandstrom U., Pajunpaa A., Klimenko V.V.* Atmospheric Optical Phenomena Caused by Powerful Rocket Launches//*Journal of Spacecraft and Rockets*. 2000. V. 37. No. 6. P. 812-821.

6.*Mendillo, M., Hawkins, G. S., and Klobuchar, J. A.* A Sudden Vanishing of the Ionospheric F Region due to the Launch of Skylab//*Journal of Geophysical* Research. 1975. V. 80. No. 16. P. 2217-2228.

7.*Karlov V.D., Kozlov ?.?., Tkachev G.N*. Large-scale indignations in an ionosphere, rockets arising at flight with working engine (review)//Space researches (Space Researches, Russia). 1980. V. 18. No. 2. P. 266-277.

8.*Krasovskij V.I., Rapoport Z.T., Semenov A.I.* New emissions in the upper atmosphere as result of artificial influence on an ionosphere//Space researches. 1982. V.20. No.2 P.237-243.

9.*Platov J.V., Semenov A.I., Shefov ?.?.* Increase of intensity of hydroxyls emission in the mesopause, connected to injection of rocket combustion products//Geomagnetism and aeronomy (Geomagnetizm I aeronomija, Russia). 2001. In a seal.

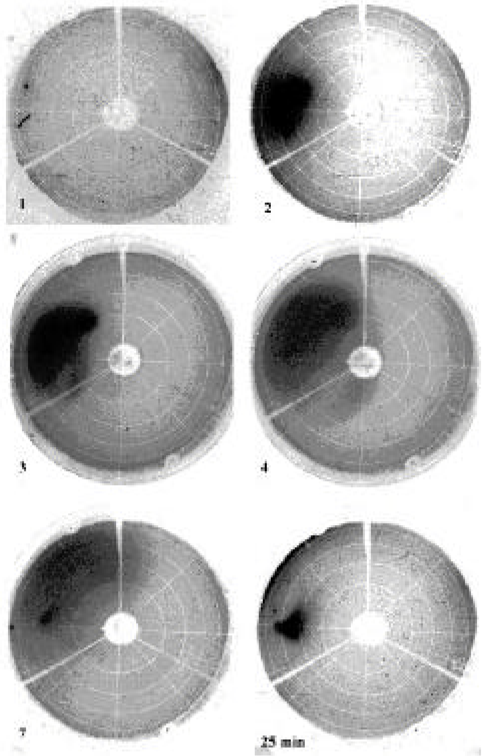

Fig. 4: All-sky images of the development of the gas and dust cloud formed during the shut off of a solid fuel rocket engine.The elapsed time in minutes after initial discovery of the luminous cloud is given in each frame. The first frame shows the rocket plume.The last frame shows rocket exhaust gas components left after rocket engine shut off.

10.Allen C.W. Astrophysical quantities. 1973. University of London.

11.Environmental problems and risks of influences of space-rocket engineering on environmental natural environment. The handbook. Moscow. Publishing house ANKIL. 2000.

12.*Oberg J.E.* The Great Soviet UFO Coverup//*UFO Journal (USPS 002-970) 103 Oldtowne Rd.Seguin, Texas* 78155. 1982. P.1-10.

13.*Platov Ju.V., Rubtsov V.V.* UFO and Modern Science. 1991.Moscow. Nauka.236p.

14.*Smirnova N.V., S.I.Kozlov S.I., Kozik ?.?.* Influence of launches of solid fuel rockets on an ionosphere of the Earth. 2. Areas ?, E-F//Space researches. 1995. V. 33. No. 2. P. 115.

15.*Wu J.C.* Possible Water Vapor Condensation in Rocket Exhaust Plumes//*AIAA Journal*.1975. V. 13. No. 6. P. 797-802

16.*Pike C.P., Knecht R.A., Viereck R.A., Murad E., Kofsky I.L., Maris M.A., Tran N.H., Ashley G., Twist L., Gersh M.E., Elgin J.B., Berk A., Stair A.T., Bagian J.P. and Buchli J.F.* Release of Liquid Water from the Space Shuttle//GRL. V. 1. No. 2. P. 139-142.