JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 41, No. 4, July–August 2004

Classification of Gas–Dust Formations from Rocket Exhaust in the Upper Atmosphere

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The results of research into the optical phenomena produced by rocket exhaust products in the upper atmosphere are presented. The data were obtained during routine observations of auroras by all-sky cameras from 1975 to 1990 from the Kola peninsula and Arckchangelsk region. The observed rocket launches were carried out from the Plesetsk and White Sea launch sites during both nighttime and twilight periods. The observed phenomena can be divided into two main types: local phenomena with long development times and relatively short-lived large-scale ones. The characteristic properties of both types are determined, in the first instance, by the type of rocket engines used (solid or liquid propellant) and their operating mode. The most intense, large-scale and dynamic phenomena are caused by separation of rocket stages and shutoff of solid-fuel rocket engines.

Introduction

UNTIL recent times, studies of rocket exhaust effects on the environment were classified. During recent years, however, it has been understood that the consequences of technical activity might have a global character. This has resulted in establishing international projects aimed at studying the ecological consequences of the environment from rocket launches. One line of investigation is the study of upper-atmosphere disturbances produced by rocket-engine operations.

The launch of powerful rockets and the exhaust 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–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. Unlike the optical phenomena accompanying rocket launches into the lower and middle atmosphere, the phenomena appearing in the upper atmosphere are unique because at heights over 100 km almost no dispersed particles of natural origin are found.

Investigation of these optical phenomena permits studies of anthropogenic pollution of near-Earth space, interaction processes of pollution with the environment, and dynamic processes in the upper atmosphere.

Analysis and Discussion

The optical signatures in the upper atmosphere accompanying rocket launches made from the Plesetsk cosmodrome and White Sea rocket ranges have been recorded for many years by all-sky cameras in the northwest regions of the former Soviet Union as part of normal aurora recordings. Over 50 rocket plumes and large-scale diffusive formations have been captured on photographic film. For the standard mode of photography, pictures were taken once every 5 min or once per min with an exposure time of 5 or 20 s. With a film sensitivity of 400 ASA, it was possible to register luminous objects with a brightness of more than $\sim 10^{-8}$ stilb (sb).

Investigations into the dynamic and structural features of the most interesting large-scale artificial formations in the upper atmosphere have been carried out in a number of papers.[1–5] In particular, it has been shown that the characteristic velocity of expansion of gas–dust clouds formed by rocket exhausts is 1–2 km s^{-1}, and their sizes can reach several hundreds of kilometers in diameter. Interaction of the gas phase of combustion products with the atmospheric components results in changes of the ion-molecular reactions that also can result in the occurrence of anomalies in luminescent phenomena of the upper atmosphere.[6,7] Analysis of the optical recordings gives a general estimation of the lifetime of the phenomena as well as conclusions as to the physical mechanisms involved.

In general, it is possible to divide the large-scale optical upper-atmosphere phenomena into a few basic classes:

1) The first class is turbopause phenomena at a 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 a rather high brightness and frequently are observed visually from distances up to 1000 km away. The expansion speed of such formations is about 2 km s^{-1} with a characteristic cross-sectional size of 100–200 km. The location of these phenomena at 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 $\boldsymbol{m}\,\mathbf{d}\boldsymbol{t} = \boldsymbol{\pi r^2 V^2 \rho}\,\mathbf{d}\boldsymbol{t}$, where $\boldsymbol{m} = \boldsymbol{4\pi r^3 \rho_0/3}$ is the mass of a particle, ρ_0 is the particle density, $\boldsymbol{r}$ is its radius, $\boldsymbol{V}$ is its velocity, and $\boldsymbol{\rho}$ is the atmospheric density. The particle's change in velocity is given by $\boldsymbol{V} = \boldsymbol{V_0/(1 + 3\rho V_0 t/4\rho_0 r)}$, and its characteristic braking distance, that is, the e-folding distance, is given by $\boldsymbol{L} = \boldsymbol{4\rho_0 r/3\rho \ln(1 + t/\tau)}$, where $\boldsymbol{\tau} = \boldsymbol{4\rho_0 r/3\rho V_0}$. Figure 1 shows the variation in braking distance with altitude for 1-μ size particles for the model atmosphere given in Ref. 8.

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

Received 12 November 2002; revision received 21 July 2003; accepted for publication 21 July 2003.

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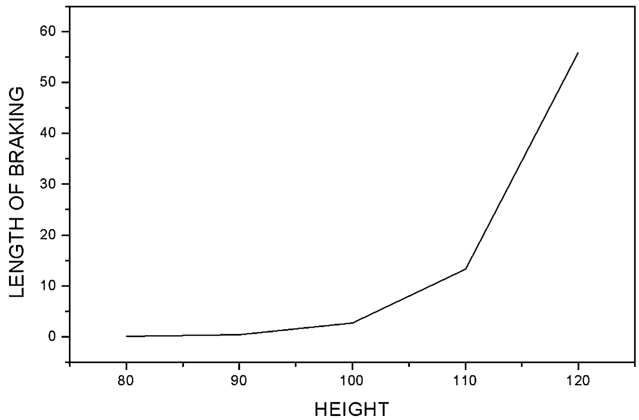

Fig. 1 Characteristic braking distance of 1-μ particles with altitude.

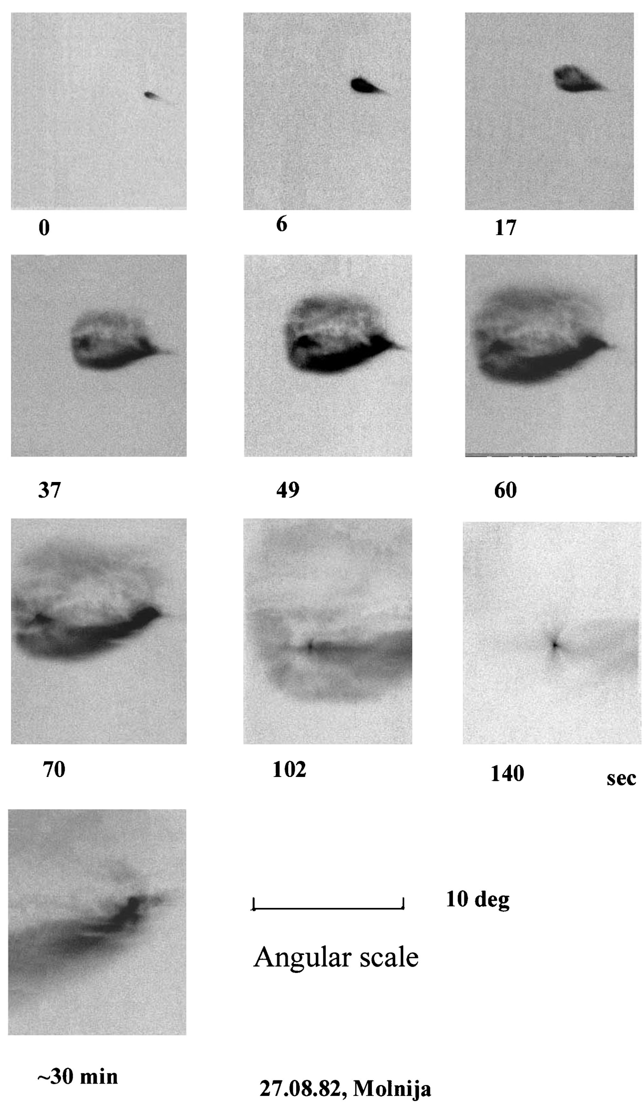

Fig. 2 Negative images of the gas and dust cloud development of rocket exhaust products during launch of the Molniya satellite from Plesetck.

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. Figure 2 shows the development of the gas and dust cloud at 100–130 km formed during the launch of a Molniya satellite. The phenomenon was recorded from a place located close to the rocket start position. 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 ninth frame (140 s) 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 analogous phenomenon observed sideways from distance about 800 km is shown on Fig. 3. 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]

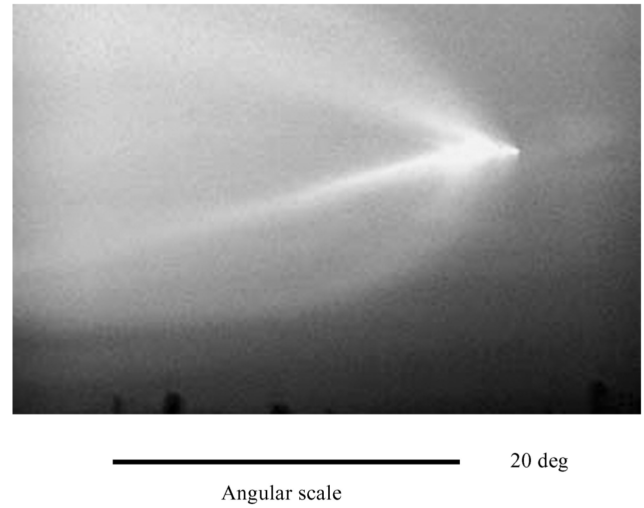

Fig. 3 Photo of gas–dust rocket tail analogous to Fig. 2 but recorded sideways from distance about 800 km.

2) Large-scale dynamic phenomena at 150 km or higher is the second class. These phenomena are connected to special modes of rocket-engine operation, in particular, shutoff 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 the matter injected into the atmosphere is a function of the combustion chamber pressure, volume, and temperature: $\boldsymbol{M} = \mu \boldsymbol{PV}/\boldsymbol{RT}$, where $\boldsymbol{P}$ is pressure, $\boldsymbol{V}$ is volume, $\boldsymbol{T}$ is temperature, and $\boldsymbol{\mu}$ is the average molar weight of the exhaust products. For typical values of $P = 10$ MPa, $V = 20\ m^3$, $T = 2800$ K, and $\mu = 0.035$ (Ref. 9), the mass released is $\sim$300 kg. In exceptional cases such artificial clouds can rise up to 700 km altitude, and their cross-sectional size can exceed 1500 km (Ref. 2) with an expansion rate of 2–3 km s^{-1}. 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, that is, the turbopause boundary. These rocket trails have been widely observed not only in Russia, but also around the world during powerful solid-fuel rocket launches. Figures 4 and 5 show two examples of the development of high-altitude gas–dust clouds taken with an all-sky camera. The elapsed time in minutes after the initial appearance of the luminous cloud is given in each frame. In the first case the expanding cloud was formed during shutoff of the solid-fuel rocket engines at the height of 150 km. The first frame of Fig. 4 shows the track of the rocket plume. Frames 2–5 correspond to dynamic expansion of the gas–dust cloud. The last frame shows rocket-exhaust gas–dust components left near the turbopause after rocket engine shutoff. After the last image the shape of the cloud did not change almost up to sunrise. The images of Fig. 5 have the same character but show the effect of particle velocity dispersion in the form of a torus shape.

3) One more class of rather weak optical phenomena are the large-scale conical formations behind working rocket engines at large enough heights under dark night conditions. Their characteristic size is 200–400 km (Refs. 4 and 10). The observed features of such phenomena are determined by the scattering of sunlight on

Table 1 Optical phenomena resulting from rocket launches through upper atmosphere

Parameter of gas-dust cloud	Long-lifetime luminous formations	Short-lifetime luminous formations	Conical luminous formations
Height of artificial cloud	100–120 km	100–700 km	>1000 km
Characteristic size	~100 km	100–1000 km	200–400
Formation lifetime	0.1–6 hours or more	1–10 minutes	During rocket-engine operation
Type of spectrum	Discrete lines and molecular bands	Continuous emission	Continuous emission
Brightness	Up to 10^{-6} sb	Up to 10^{-4} sb	Up to 10^{-6} sb
Cloud structure	Molecular gas components of rocket exhaust	Dispersed solid particles from the rocket exhaust with 0.1–10-μ characteristic sizes	Ice particles condensed in rocket jet
Luminosity mechanism	Mostly resonant scattering of sunlight as well as interaction of combustion productions with atmospheric constituents	Scattering of sunlight by dispersed particles	Scattering of sunlight by ice particles condensed in rocket jet
Dynamic development of the cloud	Molecular diffusion[12]	Spreading of dust cloud	Spreading of ice cloud and sublimation of particles

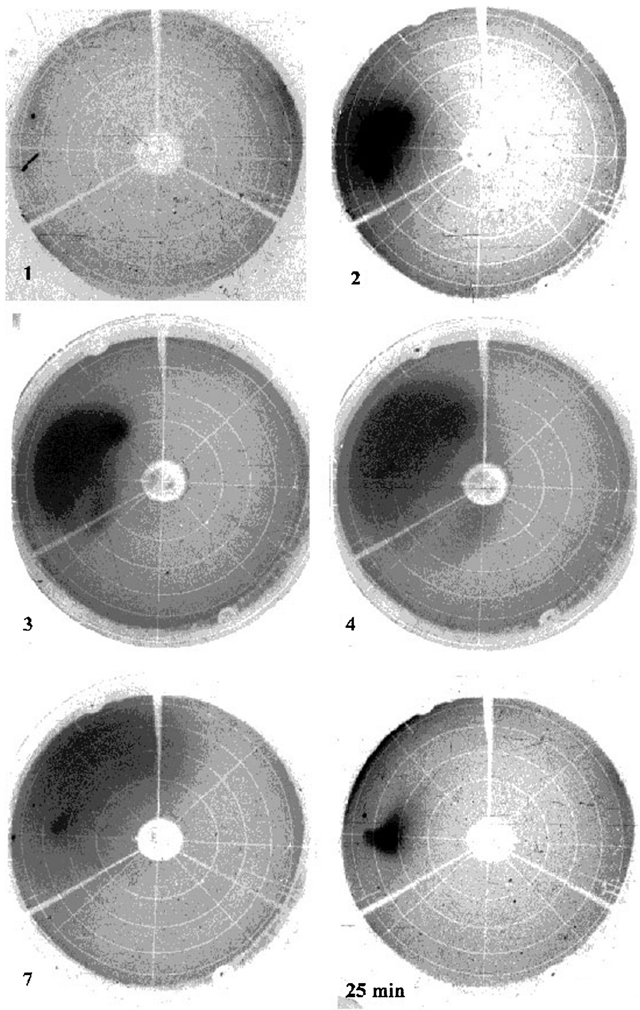

Fig. 4 Negative images. The solar zenith angle is ~106 deg at the first frame and ~101 deg at the last one.

ice particles condensed in the rocket exhaust jet. The conical shape of this formation corresponds to the expansion of rocket exhaust products, and its size depends on the lifetime of ice particles and their sublimation rate. For typical conditions prevailing in the upper atmosphere, this time is about 100–200 s (Ref. 11). As the expansion velocity of combustion products is ~3 km s^{-1}, the characteristic size of the conical formation of ~200–400 km is in accordance with the sublimation time. Very likely these phenomena can develop at heights of ~150 km, but the luminosity of twilight and other brighter optical formations hide them.

It seems obvious that the dynamic and morphological features of the artificial clouds are a function of the relative quantities of

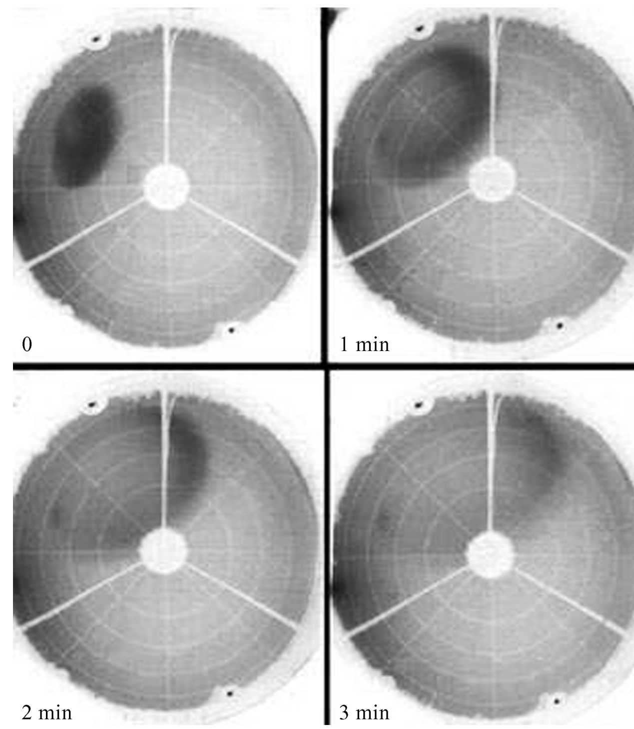

Fig. 5 Negative all-sky images of the development of rocket-exhaust gas and dust clouds. A feature of this event is the toruslike distribution of the cloud luminosity. The solar zenith angle is ~107 deg.

gaseous and dispersed solid components from the rocket exhaust. The characteristics of the basic types of optical phenomena resulting from rocket launches through the upper atmosphere are given in Table 1 (see Ref. 12).

The second class of phenomena relates to solid-fuel rocket launches exclusively because the dust of long-lived particles (Al, Al_2O_3) is contained in these exhausts only. The dispersed ice particles from the rocket exhaust are formed as the result of water vapor condensation caused by the rapid expansion of the combustion products.[1,13,14] These authors show that the observed luminosity can be explained by 5–10% of the water vapor condensing into ice crystals with a typical size of ~100 Å. 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 caused by ion-molecular interactions with the combustion products. 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 of physical and chemical interactions.

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 a rather weak diffuse luminosity remains for a long time (until sunrise stopped observations) at the location where a rocket-stage separation took place. The unique nature of these formations without any comparable natural phenomenon, their large size, and the opportunity to observe them from long distances across political boundaries has often resulted in sensational reporting in the mass media of unidentified flying objects.[15,16]

Summary

The optical phenomena in the upper atmosphere, observed at rocket launches and operation of space vehicle engines, are determined mainly by the scattering of sunlight from gas-dust "clouds" of combustion products. Long-lived clouds with characteristic sizes of ∼100–200 km are formed at heights of ∼100 km close to the turbopause. These formations consist of dispersed particles and gas components from rocket exhausts. The most dynamical, large-scale formations with lifetimes less than 10 min are observed at great heights (up to 700 km). These clouds develop due to the presence of a significant fraction of dispersed particles not evaporating (solid fuel rockets) in the combustion products. For the same class of rocket formations, it is possible to relate the phenomenon to scattering of light from ice particles condensed in the exhaust jet of space vehicles at heights more than 1000 km. The characteristic size and lifetime of such formations is determined by the rate of ice particle sublimation in the conditions of the upper atmosphere.

Acknowledgment

This study was supported by the International Scientific and Technology Center under Project 1328-99.

References

[1]Kung, R. T. V., Cianciolo, L., and Myer, J. A., "Solar Scattering from Condensation in Apollo Translunar Injection Plume," *AIAA Journal*, Vol. 13, No. 4, 1975, pp. 432–437.

[2]Tagirov, V. R., Arinin, V. A., Brändström, U., Pajunpää, A., and Klimenko, V. V., "Atmospheric Optical Phenomena Caused by Powerful Rocket Launches," *Journal of Spacecraft and Rockets*, Vol. 37, No. 6, 2000, pp. 812–821.

[3]Chemouss, S. A., and Platov, J. 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, Swedish Inst. of Space Physics, IRF Scientific Rept. 209, Kiruna, Sweden, 1992, pp. 501–505.

[4]Vetchinkin, N. V., Granitskij, L. V., Platov, J. V., and 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*, Vol. 31, No. 1, 1993, pp. 93–100.

[5]Karlov, V. D., Kozlov, C. I., and Tkachev, G. N., "Large-Scale Indignations in the Ionosphere, Rockets Arising at Flight with Working Engine," *Space Researches*, Vol. 18, No. 2, 1980, pp. 266–277.

[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*, Vol. 80. No. 16, 1975, pp. 2217–2228.

[7]Platov, J. V., Semenov, A. I., and Shefov, N. N., "Increase of Intensity of Hydroxyls Emission in the Mesopause, Connected to Injection of Rocket Combustion Products," *Geomagnetism and Aeronomy*, Vol. 42, No. 4, 2002, pp. 522–528.

[8]Allen, C. W., *Astrophysical Quantities*, Univ. of London, Athlone Press, London, 1973, pp. 179, 180.

[9]*Environmental Problems and Risks of Influences of Space-Rocket Engineering on Environmental Natural Environment*, Handbook, ANKIL, Moscow, 2000, pp. 85–89.

[10]Simmons, F. S., *Rocket Exhaust Plume Phenomenology*, Aerospace Press, El Segundo, CA, 2000, pp. 61–69.

[11]Platov, Y. V., and Kosch, M. J., "Sublimation of Ice Particles from Rocket Exhausts in the Upper Atmosphere," *Journal of Geophysical Research* (to be published).

[12]Smirnova, N. V., Kozlov, S. I., and Kozik, E. A., "Influence of Launches of Solid Fuel Rockets on the Ionosphere of the Earth. 2. Areas E, E-F," *Space Researches*, Vol. 33, No. 2, 1995, p. 115.

[13]Wu, J. C., "Possible Water Vapor Condensation in Rocket Exhaust Plumes," *AIAA Journal*, Vol. 13, No. 6, 1975, pp. 797–802.

[14]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," *Geophysical Research Letters*, Vol. 1, No. 2, 1990, pp. 139–142.

[15]Oberg, J. E., "The Great Soviet UFO Coverup," *UFO Journal*, Oct. 1982, pp. 1–10.

[16]Platov, J. V., and Rubtsov, V. V., *UFO and Contemporary Science*, Nauka, Moscow, 1991, pp. 123–136.

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Associate Editor