ISSN 0038-0946, Solar System Research, 2013, Vol. 47, No. 4, pp. 275–279. © Pleiades Publishing, Inc., 2013.
Original Russian Text © N.N. Gorkavyi, T.A. Taidakova, E.A. Provornikova, I.N. Gorkavyi, M.M. Akhmetvaleev, 2013, published in Astronomicheskii Vestnik, 2013, Vol. 47, No. 4, pp. 299–303.

Aerosol Plume after the Chelyabinsk Bolide

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Received April 1, 2013

Abstract—In this work, the bolide is studied as an atmospheric event causing significant release of meteoritic dust into the stratosphere. Ground-based pictures taken by eyewitnesses and images from the Japan geostationary satellite MTSAT-2 are used as a database. The analysis of the ground-based pictures allows the altitude of the main burst to be estimated as 22.9 ± 1.6 km. It is shown that the top of the cloud formed due to the main burst rose to 11 km for about 60–80 s due to convection, which provides an estimate of the maximum vertical velocity of 130–180 m/s. According to calculations, the upper part of the trail is affected by a strong wind drift and is located at an altitude of >53 km, in the mesosphere. The MTSAT-2 data show that the mesospheric part of the trail traveled southwestward, while the stratospheric part, northeastward, with velocities higher than 100 km/h.

DOI: 10.1134/S003809461304014X

INTRODUCTION

Meteoric dust is a typical component of the atmospheric aerosol (see, e.g., Hunten et al., 1980), which dominates at altitudes higher than 25–30 km (see, e.g., Neely et al., 2011). The amount of meteoric dust, entering the atmosphere annually, is estimated to be 10^4 t (Rosen and Ivanov, 1991). The Chelyabinsk bolide released approximately the annual amount of meteoric dust in the stratosphere and mesosphere, which should sharply change the aerosol concentration at certain latitudes. To study the atmospheric transport of meteoric dust, it is important to know altitudes of the main injections of aerosol.

Let us note that this study is based on the analysis of motions of a visible cloud of water vapor and bolide combustion products. This visible cloud does not coincide with the distribution of the dust component of the bolide plume in reality. The bolide explosion caused a supersonic expansion of the hot gas-dust cloud and the spread of small fragments and dust particles. The pressure of the expanding gas was responsible for the appearance of the component normal to the initial vector of ballistic bolide motion. In fractions of a second, the cloud expansion slowed, became subsonic, and ceased when the pressure in the cloud and in the atmosphere became equal, but the debris continued in motion, like bullets starting to move due to the expansion of combustion gases. As a result, different families of flying particles and fragments originated: very large fragments (such as the meteorite that fell in Chebarkul Lake) flew further along a ballistic trajectory close to the initial one, a number of smaller fragments experienced changes their velocity vectors and flew many kilometers in different directions from the explosion point. The smallest fragments and particles quickly decelerated in the atmosphere, were captured by the stratospheric wind, and became components of the atmospheric aerosol. Only large dust that succeeded to fall in the lower atmospheric layers, where the wind was weaker, settled to the ground in the explosion zone.

In addition to the hot gas expansion along an axis symmetrical to the bolide motion axis, vertical thermal convection and horizontal wind transport were important factors in the trail evolution.

Let us consider the altitude of the aerosol trail of the Chelyabinsk bolide and the variation in its position during first minutes and hours after the explosion.

Our analysis is based on seven high-quality images of the bolide made during the first three minutes after the explosion (Fig. 1 and the table) and pictures from the Japan MTSAT-2 satellite. Data from the ground-based pictures allow the reconstruction of the pattern of rapid variations in the gas-dust trail due to the explosive expansion of the hot cloud and its convective rise. The MTSAT-2 pictures allow an estimation of the windage velocity and the direction of the plume drift.

ALTITUDE OF THE MAIN BURST

The average altitude of the explosion, or the main burst, was equal to 22.9 ± 1.6 km for the coordinates 54.90° N, 61.11° E and has been calculated from the processing of six pictures 2–7 (see the table). The residuals of solutions for these six pictures are minimal for this geographical point. The error in the explosion point coordinates is about 0.1° in longitude and 0.05° in latitude. These values agree well with the NASA

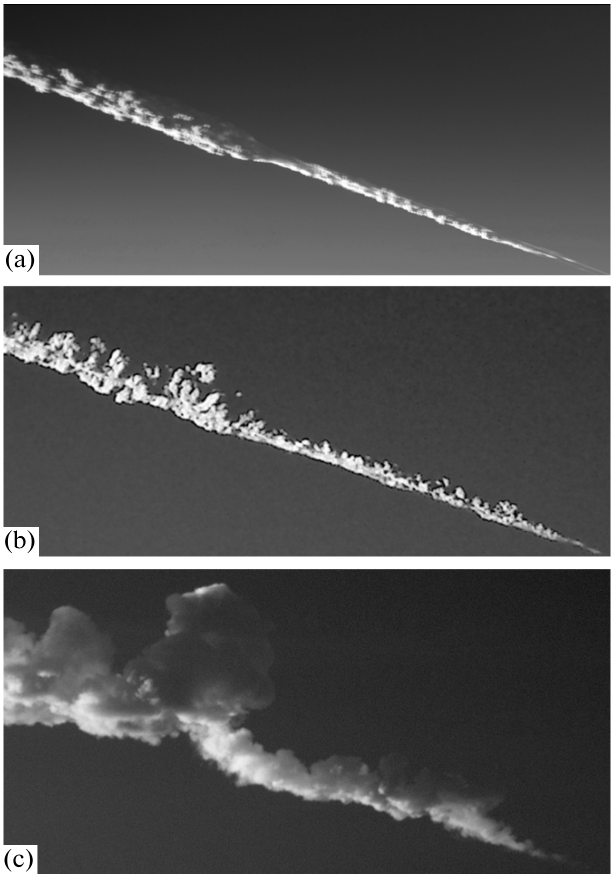

Fig. 1. Fragments of pictures 2, 3, and 4 (bottom right) at 10, 18, and 55 s after the explosion. Picture 3 is mirrored relative to the vertical axis, for convenience of perception.

data for an explosion altitude of 23.3 km and coordinates of 54.8° N and 61.1° E (Yomans, 2013). Our solution agrees with the coordinates of the main burst calculated by Borovicka et al. (2013): 54.836° N and 61.455° E, the altitude also differs significantly from that cited in the telegram, i.e., 31.73 km.

Pictures 1 and 2 were made by one of the authors of this work (M.A.). The matrix size was 5120 × 3413 pixels,

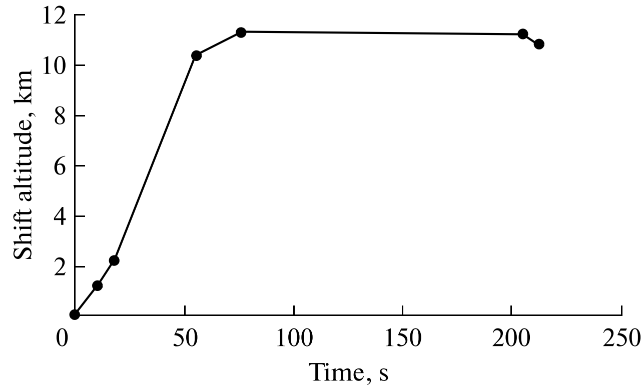

Fig. 2. Vertical shift of the cloud top relative to the main burst point.

or 35.8 × 23.9 mm; the focal lengths were 35 and 27 mm.

Picture 3 was made by K. Kudinov from the south (in contrast to other pictures made from the north). The matrix size was 2592 × 1944 pixels, or 2.97 × 2.23 mm; the focal length was 3.5 mm.

Pictures 4 and 5 were made by A. Alishevskikh. The matrix size was 5184 × 3456 pixels, or 22.3 × 14.9 mm; the focal lengths were 15 and 32 mm.

The author of pictures 6 and 7 is M. Korzhov. The matrix size was 3872 × 2592 pixels, or 21.5 × 14.4 mm; the focal length was 35 mm.

CONVECTION VELOCITY

Let us estimate the convection velocity maximum in the cloud formed at the site of the main burst. For this, we calculate the difference between the cloud altitude and the burst altitude (see the table). Figure 2 shows the cloud shift altitude as a function of time.

Let us note that inaccurate detection of the horizon in a picture is the main source of burst altitude errors. The altitude of the relative shift in Fig. 2 is independent of the error in horizon detection, because it affects the detection of burst and cloud altitudes similarly. Figure 2 shows that the velocity of vertical con-

Pictures and data used

Picture	Time after the burst, s	Surveying latitude, deg	Surveying longitude, deg	Distance to the burst point projection, km	Explosion altitude, km	Main cloud altitude, km
1	0	55.170	61.317	32.8	–	–
2	10	55.170	61.317	32.8	24.9	26.1
3	18	54.034	61.622	101.8	22.8	25.1
4	55	56.694	61.262	199.8	23.3	33.7
5	76	56.694	61.262	199.8	24.1	35.4
6	206	56.755	60.607	208.6	21.1	32.3
7	213	56.755	60.607	208.6	23.7	34.5

Fig. 3. Fragments of pictures (a) 1 and (b) 4 showing a part of the trail affected by the windage in the mesosphere differing from the stratospheric shift of the rest of the trail.

vection attained 130–180 m/s for the first 100 s, and then the cloud top point almost stopped or continued moving much more slowly, with a velocity less than 10 m/s. Note that the trail expansion was almost asymmetrical during the first 10 s (see Fig. 1), and the vertical rise of the main burst cloud became noticeable only by the 20th second. The resulting velocities of the vertical shift are typical for convective velocities of hot nuclear clouds after an explosion.

This comparison with a nuclear explosion is quite reasonable, because the volume of the cloud formed due to the main burst was close to a thousand cubic kilometers; heating such a mass of gas by tens of degrees (the air temperature increases by 20°C as the stratospheric altitude increases to 12–13 km) corresponds to energies comparable with a nuclear explosion.

ALTITUDE OF THE MESOSPHERIC PART OF THE TRAIL

A zigzag is clearly seen at the very beginning of the trail in three pictures (1, 4, and 5). Figure 3 shows the corresponding fragments of pictures 1 and 4. From these pictures, we estimated the altitude of this part of the trail as equal to 53 km for the coordinates 54.75° N and 62.55° E. Thus, the upper part of the bolide trail is located in the mesosphere. The trail zigzag means that the mesospheric wind direction and velocity differ significantly from stratospheric winds, where the main part of the bolide trail is located. According to the altitudes and coordinates found for the main burst point and the origin of mesospheric zigzag, the distance between them is 95 km. If we accept the bolide velocity equal to 18.6 km/s, calculated by NASA (Yomans, 2013), then we can find that the bolide traversed this distance for 5.1 s. Hence, the picture in the upper part of Fig. 3, made at the instant of the main burst, shows the windage of the mesospheric part of the trail, which occurred for only 5 s. Taking into account the significant distance of 100 km between the zigzag and an observer, the velocity of this shift is very high.

Two points of the bolide trajectory found allow an estimation of the angle between the trajectory projection and the 10° parallel during northwest travel. This is an important estimate; it is to help us to interpret MTSAT-2 satellite pictures.

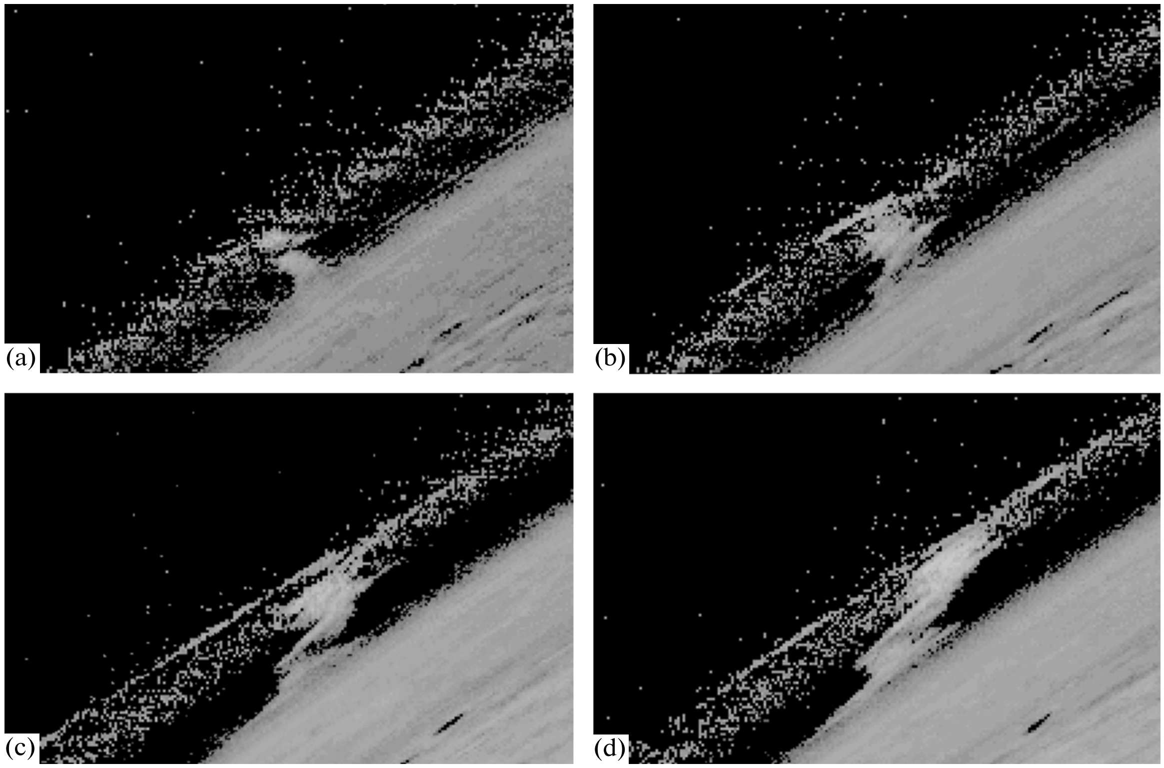

Fig. 4. Pictures of the trail of the Chelyabinsk bolide made by the geostationary MTSAT-2 satellite at (a) 12 min, (b) 41 min, (c) 72 min, and (d) 101 min after the explosion.

WINDAGE VELOCITY

Several pictures of the Chelyabinsk bolide trajectory were made from the MTSAT-2 satellite (2013) with a time step of 30 min. We used a series of MTSAT-2 pictures from the site of the University of Wisconsin (CIMSS, 2013). Figure 4 shows four pictures after computer processing and subtraction of a frame made before the burst, which increased the plume contrast. Pictures were made at 12, 41, 72, and 101 min after the burst.

The MTSAT-2 satellite followed the bolide at a small (~3°) slope of the line of sight to the direction of motion of the body (in projection on the ground). Chelyabinsk was under the horizon for the Japanese satellite. Accepting a value of 145° for the MTSAT-2 longitude, we find that only a part of the trail above 23.8 km is seen above the horizon.

The variations in the cloud detail positions allow the conclusion that the mesospheric part of the trail traveled southeastward with a velocity of 90–95/sin(A) km/h (A is the angle between the cloud direction and the line of sight equal to 90° during perpendicular motion), while the rest of the trail, apparently belonging to the stratosphere, travels northeastward, and the most mobile part of the stratospheric part of the trail travels approximately with the same high velocity (in projection) as the mesospheric part. At any reasonable estimates of the angle A, the real velocity of these quickly moving trail parts noticeably exceeds 100 km/h. The denser and lower part of the trail (see Fig. 4) travels northeastward with a much lower velocity of ~30–40/sin(A) km/h. Such a sharp difference between the velocities of the stratospheric wind with a change in altitudes by only several kilometers is not something exceptional.

CONCLUSIONS

The analysis of ground-based pictures allows the altitude of the main burst to be estimated as 22.9 ± 1.6 km. The cloud that originated from the main burst rose with a vertical velocity of >100 m/s due to convection. The cloud reached an altitude 11 km higher than the burst point for 1.5 min.

According to the analysis, the upper part of the bolide trail is located in the mesosphere at an altitude of >50 km. The stratospheric and mesospheric parts of the bolide plume were immediately affected by strong windage in the northeast and southwest directions, respectively.

The study of the formation and convective and wind transport of the aerosol trail of the Chelyabinsk bolide is important for the simulation of aerosol propagation, as well as for the study of the atmosphere.

In future authors are going to use additional satellite and onground photos and totally restore 3D picture for bolide plume evolution within the first hours.

ACKNOWLEDGMENTS

The authors would like to thank Maksim Korzhov, Aleksei Alishevskikh, and Konstantin Kudinov for the pictures of the bolide trail provided for the study.

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Translated by O. Ponomareva