THE PHYSICAL EFFECTS ASSOCIATED WITH CHELYABINSK METEORITE'S PASSAGE

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The main effects associated with the February 15, 2013 Chelyabinsk bolide (Chebarkul meteorite) have been estimated. The major amount of energy release (approximately 0.2 Megaton) occurred near 25 km altitude where the rate of mass loss attained 20 kiloton s^{-1}, and the optical emission energy of 375 TJ. The pressure behind the shock near the bolide explosion epicenter attained a few kilopascals. The surface area of partial destructions was equal to approximately 6,000 km^2. The bolide explosion gave rise to appreciable disturbances not only in the lower atmosphere, but also in the upper atmosphere at a range of not less than 1,000…2,000 km. The effects in the geomagnetic field reached 0.5…1 nT. The earthquake caused by the bolide explosion had a Richter magnitude of 3-4.

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INTRODUCTION

The passage of the Chelyabinsk meteorite over an inhabited area on February 15, 2013 that was associated with a series of shock waves and flash of bright light has been the most hazardous impact of an asteroid over the last century. It caused more than 1.600 injuries, mainly by glass from about 20.000 m^2 shattered panes of glass, and caused damage to over 3.000 buildings over Chelyabinsk province. It did over $30.000.000 worth of damage. Because of the uniqueness of the event and its consequences, the detailed and comprehensive study of the effects caused by an impacting asteroid of large enough mass is of great importance [1 - 4].

The meteorite entered the atmosphere at 03:20:26 UT on February 15, 2013. It moved from south-east to north-west at an azimuth of about 270° and at an elevation of approximately 20°. The meteorite had an approximate mass of 11 kilotons, a speed of 18.5 $km \cdot s^{-1}$, and a diameter of 18 m before it entered the denser parts of Earth's atmosphere [5]. The collected samples allowed the classification of the meteorite as LL5 hondrite containing metallic iron, olivine, and iron solfide minerals. The fragments are scattered over a wide area near Lake Chabarkul.

The interaction of large meteoroids with the atmosphere is dealt with in a few studies (e.g., [6 - 9]). These papers investigate the features of meteorite movement and disintegration in the atmosphere.

The purpose of this paper is to theoretically estimate the major effects associated with the Chelyabinsk meteorite's passage and to compare the estimates with observations.

1. PHYSICAL PROCESSES ASSOCIATED WITH METEORITE'S PASSAGE

The passage of large meteorites is associated with a series of physical processes (e.g., [6]).

The meteorite kinetic energy is transferred to a bow shock in the atmosphere. The air temperature behind the shock increase, the molecule vibrational levels are excited, molecule dissociation and ionization occur, i.e. a plasma is created. A fraction of the kinetic energy of the air particles behind the shock is transferred to the meteorite via the convective heat transfer. The plasma electrons impart their energy to the meteorite via the thermal conductivity. The hot air emits electromagnetic waves in a large frequency band.

The electromagnetic energy accounts for meteorite heating and evaporation, meteorite vapor heating and expansion, and air heating and ionization in front of the bow shock. The ablative shock at the surface of the meteorite exposed to a pulse of intense electromagnetic radiation propagates through the material and can cause melting, vaporization, spallation, and structural failure of the object. The optical emissions from excited atmospheric species are not absorbed and lost.

The ballistic wave ahead of the meteorite is spread around. The shock wave reaching the Earth's surface causes mechanical damage and destruction. The flash of bright light causes heating, skin burns, and even fires.

The meteorite fragments moving at subsonic speed fall on the Earth's surface.

The passage of large (diameter of more or equal to 10…20 m) meteorite results in the formation of a heated track. At the final stage of deceleration, the blast products reach the higher altitudes along the track and form a plume [2].

The thermal, shock, plume, and wave processes occurring during a meteorite's passage are associated with magnetic, electric, acoustic, and seismic disturbances.

2. THE RESULTS OF CALCULATIONS

General Information. The passage of a meteorite through the Earth's atmosphere is described by the well-known equations for deceleration, mass loss, changes in elevation, height, and luminosity (e.g., [6, 9]). These equations were solved numerically, taking into account meteorite fragmentation. The initial meteorite shape was considered to be nearly spherical. The drag coefficient (C_D = 1), the heat transfer coefficient (C_h = 0.02), and the luminosity factor (τ = 0.2) were assumed to be constant. The latent heat of sublimation was assumed to be equal to 1.5 MJ kg^{-1}. The atmospheric state was assumed to vary in an exponential manner with a neutral scale height H of 7.5 km.

The initial kinetic energy of the meteorite was appeared to be equal to $1.88 \cdot 10^{15}$ J, which is equivalent to energy released by 0.44 megatons of TNT or 35 Hiroshima bombs.

The major amount of energy was released in a layer of thickness approximately 22 km, with the mean rate of energy release to be $8.5 \cdot 10^{10}$ $J \cdot m^{-1}$, the characteristic time scale of energy release 1.2 s, and the characteristic power of the process 1.6 PW.

Table 1

Altitude dependences of atmospheric density, main bolide kinematics' and energetic parameters (E_k is the bolide kinetic energy, P is the power of bolide deceleration)

z (km)	18	19	20	21	22	23	24	25	27	30	35
ρ (kg m^{-3})	10^{-1}	$8.6\cdot10^{-2}$	$7.3\cdot10^{-1}$	$6.5\cdot10^{-2}$	$5.3\cdot10^{-2}$	$4.9\cdot10^{-2}$	$4.1\cdot10^{-2}$	$3.4\cdot10^{-2}$	$2.4\cdot10^{-2}$	$1.6\cdot10^{-2}$	$8\cdot10^{-3}$
S (m^2)	$7.5\cdot10^4$	$6.3\cdot10^4$	$5.2\cdot10^4$	$4.36\cdot10^4$	$3.6\cdot10^4$	$3\cdot10^4$	$2.4\cdot10^4$	$2\cdot10^4$	$1.25\cdot10^4$	$5.8\cdot10^3$	922
v (km s^{-1})	0.07	0.45	1.7	4.6	8.3	11.6	14.3	15.9	17.6	18.4	18.5
m (kT)	3.50	3.50	3.54	3.76	4.41	5.50	6.94	8.16	9.87	10.9	11.0
$-\frac{dm}{dt}$ (kT s^{-1})	$1.7\cdot10^{-5}$	$3.3\cdot10^{-3}$	0.1	1.84	7.82	15.3	19.2	18.2	10.9	3.85	0.3
E_k (TJ)	$8.6\cdot10^{-3}$	0.35	5.1	40	152	370	710	1030	1530	1845	1880
P (PW)	$1.32\cdot10^{-6}$	$2.47\cdot10^{-4}$	$9.49\cdot10^{-3}$	$1.58\cdot10^{-1}$	$8.57\cdot10^{-1}$	2.18	3.29	3.68	2.53	$9.38\cdot10^{-1}$	$7.59\cdot10^{-2}$

Meteorite Disintegration. In the upper part of the trajectory, the stony meteorite suffered flaking, and between 20- and 35-km altitude fragmentation. The meteorite initially had spherical shape, which was gradually changing into a pancake shape, with a gradually increasing midsection. The fragmentation products moved forward like a quasi-liquid.

A meteorite destructs when the dynamic pressure becomes equal to the material strength. The different parts of a meteorite have different strength, σ, since the material strength of a stony meteorite changes in a wide range from 10^6 to 10^7 N·m^{-2} [2]. The condition for disintegration occur at the altitude where the atmosphere density ρ varies from $5.8\cdot10^{-3}$ to $5.8\cdot10^{-2}$ kg·m^{-3}, which corresponds to the altitudes of 37…22 km. The fragmentation of the bolide is assumed to begin at an altitude z_0 of 37 km, and ceased at 20 km.

Since the onset of fragmentation, the products moved forward like a quasi-liquid, acquiring a lateral speed of order of 1…10 m·s^{-1}.

Estimates of the midsection S, the bolide speed v, and the rate of mass loss dm/dt are presented in the Table 1. Table 1 shows that the main mass loss occur between 23 km and 27 km altitude.

Optical Emissions. The U.S.A. geostationary satellite sensors [5] have estimated the total emission energy E_r of approximately $3.75\cdot10^{14}$ J. The 1.2 s effective duration of the radiation pulse results in a 313 TW peak power.

Estimates of the optical emission energy flux. If the emission emanates from a flat surface area of $4\cdot10^4$ m^2, the flux density is equal to $7.8\cdot10^9$ W m^{-2}. Taking into account absorption in the atmosphere reduces the flux density to $1.9\cdot10^4$ W·m^{-2} at the center. The flux density of the light is more than an order of magnitude greater than the optical solar flux of 500 W m^{-2}. The equivalent black body temperature is equal to $1.9\cdot10^4$ K, with a peak emission wavelength of $1.5\cdot10^{-7}$ m. In fact, thermal radiation is generated within the volume of the object, but not on its surface. In any case, its temperature is of order of 10^4 K.

Given an E_r value, an estimate can be made whether the bolide could create a fire risk. Near the epicenter, the energy flux from the fire ball was approximately equal to $1.8\cdot10^4$ J·m^{-2}, whereas dry matter ignites when the energy flux equals to $(2…10)\cdot10^4$ J·m^{-2}. Therefore, fires at Chelyabinsk did not occur.

Shock Parameters. The explosion was assumed to occur at altitudes near 25 km (Table 1). The shock radius R_s is approximately equal to 0.43 km when a cylindrical symmetry of explosion is adopted. The cylindrical shock in the exponential atmosphere creates a pressure increase Δp of approximately 2.4 kPa beneath the epicenter. Table 2 provides dependence of Δp on the cylinder radius R, where R_0 is the distance from the epicenter along the Earth's surface. As can be seen from Table 2, the shock remains strong enough to cause partial destructions up to a range of 100 km. Table 2 also provides a pressure increase Δp_s for spherical symmetry of the shock. Partial destructions occur over an area of approximately 6.000 km^2 at a level of 1 kPa in a pressure increase.

The propagation of the shock upwards disturbed the upper atmosphere. Table 3 shows the altitude dependence of an increase in pressure Δp (z). As can be seen from Table 3, the pressure increase in the shock rapidly decreases with increasing altitude, whereas the pressure increase relative to the ambient pressure above 50 km altitude increases with increasing altitude. In reality, a pressure increase should be smaller because the calculations have not accounted for shock energy dissipation.

The shock energy propagates in the horizontal direction. For radial outflow in a spherical geometry, the relative increase in pressure of order of unity is expected to be observed at an altitude of 300 km at a range of 1,000 km. However, the wave can be ducted in atmospheric waveguides, resulting in an appreciably greater increase in pressure.

Acoustic Effects. A bolide moving in the atmosphere induces perturbations on frequency scales from acoustic frequencies of 1 kHz to internal gravity wave frequencies of $10^{-3}…3\cdot10^{-3}$ Hz. Prior to the bolide explosion, 1% ($1.9\cdot10^{13}$ J) and 5% ($9.4\cdot10^{13}$ J) of the kinetic energy of the bolide is converted into acoustic and internal gravity wave energy, respectively (e.g., [4, 11]). As the bolide explodes, 30% of the kinetic energy is converted into the shock wave [2], i.e., approximately $5.6\cdot10^{14}$ J. At a range far enough, the shock energy is converted into the energy of atmospheric gravity waves.

Table 2

Distance dependence of the shock pressure ($S_d = \pi R_0^2$ is the surface area of damage and destruction)

R (km)	25	30	40	50	60	70	80	90	100
R_0 (km)	0	16.6	31.2	43.3	54.5	65.4	76	86.5	96.8
Δp (kPa)	2.4	2	1.9	1.7	1.5	1.4	1.3	1.26	1.2
Δp_s (kPa)	2.4	1.8	1.3	1	0.9	0.75	0.66	0.59	0.53
S_d (km^2)	0	855	$3.1\cdot10^3$	$5.9\cdot10^3$	$9.3\cdot10^3$	$1.6\cdot10^4$	$1.8\cdot10^4$	$2.3\cdot10^4$	$2.9\cdot10^4$

The period of the gravity wave with the greatest amplitude is related to the energy of the source. Estimates showed a value near 21 s. This estimate is valid for explosions at the air-earth boundary. For explosion at 25 km altitude, the wave period is equal to approximately 63 s. Approximately the same periods (near 55 s) were observed at an infrasound observatory in Kazakhstan [12]. The waves with a maximum period of 4.5 min were propagated at large distances (up to a global scale) [4]. Almost 10% of the explosion energy was converted into their energy.

Effects in the Ionosphere and Magnetosphere. A shock acts to create a moving increase in the electron density N. The relative disturbance in the density is approximately equal to the relative disturbance in pressure. The shock is a source of the traveling ionospheric disturbances in the atmospheric gravity waveband (e.g., [4, 13]).

The nonstationary plasma in the geomagnetic field at the wake of the bolide is a source of magnetohydrodynamic waves that can propagate in the ionosphere and magnetosphere. The interaction of these waves with the electrons in Van Allen belts can result in the electron precipitation in the atmosphere [4, 14].

Geomagnetic Effects. The geomagnetic effect of meteorites is poorly studied. The mechanisms listed in [15] for generating geomagnetic disturbances cannot be considered effective. The major mechanism is the modulation of the electrojets in the ionosphere by atmospheric gravity waves induced by the explosion and generating dynamo electric fields in the 100…150 km altitude region (e.g., [13]).

Estimates show that an atmospheric gravity wave with a 60-s period and a relative disturbance in the density equal to unity generates the current density of $10^{-7}…(2\cdot10^{-7})$ A·m^{-2} and geomagnetic pulsations with amplitudes of 0.5…1 nT.

Electric Field Effects. The electric potential difference between the layer in the altitude range from 25 to 45 km and the ground is equal to 4.5…45 MV, the electric charge of the object 4…40 mC, and the electric field intensity 0.5…5 MV·m^{-1}. The energy of lightning discharge and acoustic disturbance did not exceed a few MJ and hundred joules, respectively.

The Electrophone Effect. This effect arises from lightning discharge and the "demodulation" of radio emissions from the bolide's plasma wake in the 1…10 kHz range of frequencies. Estimates showed that the intensity of the acoustic emissions at the ground attained a value of 70 dB.

Seismic Effects. When the shock surface area is assumed to be 100 km^2 at the ground, the shock energy is equal $3\cdot10^{14}$ J. A $10^{-5}…10^{-4}$ fraction of the shock energy from an explosion at the ground is converted into the energy of seismic waves [4], which gives seismic wave energy of $(3\cdot10^9)…(3\cdot10^{10})$ J. This energy corresponds to a Richter magnitude of 3.1…3.8. Man does not practically perceive an earthquake of Richter magnitude 3.2…4 [16, 17].

Thus, the Chelyabinsk bolide caused a variety of phenomena in the atmosphere and magnetosphere, i.e. in the Earth-atmosphere-ionosphere-magnetosphere system as a whole [14].

The Rate of Entering the Atmosphere by Space Objects. The rate at which space objects enter the atmosphere depends on their energy (mass and speed). The well-known relation (e.g., [4, 10]) shows the number of objects entering the atmosphere during the year.

For an object similar to the Chelyabinsk bolide, this relation yields an approximate average impact interval of 65 years.

3. OBSERVATIONS

The observations were made from the Kharkov V.N. Karazin National University Radiophysical Observatory (the distance from Kharkiv to Chelyabinsk is approximately equal to 1750 km). Quasi-periodic disturbances with a delay of approximately 70 min, peroids of 3 min and 150 min, and disturbance amplitude of 10 and 30%, respectively, have been detected in the lower ionosphere and in the bottom side of the F2 region. These disturbances were due to acoustic and gravity waves. An increase in the electron density was observed at the 250-km altitude with time delays of approximately 6…7 h. If this increase is caused by the bolide, the direct cause of the disturbance can be the plume and subsystem coupling in the Earth-atmosphere- ionosphere-magnetosphere system.

The disturbance in the geomagnetic field did not exceed 1 nT.

Table 3

Altitude dependence of the shock pressure, scale height H, and the undisturbed atmosphere pressure

z (km)	30	40	50	60	70	80	90	100	200	300
$2H$ (km)	15	15	15	15	15	15	15	21.7	87	90
Δp (kPa)	720	220	18	6.7	2.7	1.1	0.5	0.2	$2.7\cdot10^{-4}$	$5.5\cdot10^{-4}$
p_0 (kPa)	$1.8\cdot10^3$	480	130	33.5	8.8	2.3	0.6	0.16	$1.6\cdot10^{-3}$	$1.6\cdot10^{-4}$
$\Delta p/p_0$	0.40	0.46	0.14	0.20	0.31	0.48	0.83	1.25	16.9	34.4

CONCLUSIONS

1. The passage and explosion of the Chelyabinsk bolide (a small asteroid) caused appreciable (or strong) disturbances in all geospheres. The altitude of the Chelyabinsk object explosion is determined to be equal to approximately 25 km.

2. The excess pressure at the ground near the explosion epicenter was equal to a few kPa. This pressure disturbance is large enough to cause destruction of structures over a surface area of 6,000 km^2.

3. The flash of light energy and power were equal to approximately 375 TJ and 313 TW, respectively. The flux was one or two orders of magnitude lower than that needed to set fire to substances and start fires.

4. The shock and acoustic oscillation energy was equal to 560 TJ and 19 TJ, respectively.

5. A Richter magnitude of the earthquake induced by the Chelyabinsk object did not exceed 3-4.

6. Relative neutral pressure and electron density disturbances at ionospheric heights over the explosion epicenter attained hundreds of per cent.

7. The geomagnetic disturbance in the vicinity of the Chelyabinsk object explosion was equal to 0.5…1 nT.

8. Appreciable disturbances from the explosion were propagated in the horizontal direction over a distance range of a few thousand kilometers.

9. Space objects similar to the Chelyabinsk bolide (tiny asteroid) enter the Earth's atmosphere one time each 65 years.

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ФИЗИЧЕСКИЕ ЭФФЕКТЫ ПРОЛЕТА ЧЕЛЯБИНСКОГО МЕТЕОРИТА

Л.Ф. Черногор, В.Т. Розуменко

Оценены основные эффекты, сопровождавшие падение Челябинского болида (Чебаркульского метеорита) 15 февраля 2013 г. Показано, что основное энерговыделение (около 0.2 Мт) имело место вблизи высоты 25 км, где скорость потерь массы достигала 20 кт/с, энергия оптического свечения – 375 ТДж. Вблизи эпицентра взрыва болида давление во фронте ударной волны составляло единицы килопаскалей. Площадь зоны частичных разрушений построек была близка к 6 тыс. км^2. Взрыв болида привел к заметному возмущению не только нижней, но и верхней атмосферы на удалениях не менее 1…2 тыс. км. Величина геомагнитного эффекта составила 0.5…1 нТл. Магнитуда землетрясения, вызванного взрывом болида, не превышала 3-4.

ФІЗИЧНІ ЕФЕКТИ ПРОЛЬОТУ ЧЕЛЯБІНСЬКОГО МЕТЕОРИТА

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Оцінено основні ефекти, що супроводжували падіння Челябінського боліда (Чебаркульського метеорита) 15 лютого 2013 р. Показано, що основне енерговиділення (близько 0.2 Мт) мало місце близько висоти 25 км, де швидкість втрати маси досягала 20 кт/с, енергія оптичного свічення – 375 ТДж. Близько епіцентру вибуху боліда тиск у фронті ударної хвилі становив одиниці кілопаскалей. Площа зони часткових руйнувань будівель була близька до 6 тис. км^2. Вибух боліда призвів до помітного збурення не лише нижньої, а й верхньої атмосфери на віддаленнях не менше 1…2 тис. км. Розмір геомагнітного ефекту склав 0.5…1 нТл. Магнітуда землетрусу, викликаного вибухом боліда, не перевищувала 3-4.