Impacts of differently-sized cosmic bodies have been playing a significant role in the evolution of the Earth. Kilometer-sized and larger comets and asteroids produce craters, cause displacements of large masses of the Earth’s crust material, [1] and can result in global climate changes and mass extinctions of biota [2]. Numerous traces of crater-forming impacts are being examined by geologists. However, such events are rather rare, kilometer-diameter bodies strike the Earth once per 600,000 years [3].

On the other hand, meteoroids with sizes of several meters and smaller are permanently observed. Impacts of these bodies result in light flashes in the sky (meteor phenomena), sometimes in the fall of meteorites and formation of small craters and crater fields [4]. These events are the subject of meteor physics. The impacts of meter-sized and smaller meteoroids do not lead to any significant effects on the Earth’s surface and do not leave any traces in the geologic history of the planet.

There is an intermediate and rather poorly studied class of events, aerial bursts, associated with “burning out” of comparatively large (from tens of meters to a few hundred meters) cosmic bodies in the atmosphere [5]. The aerial bursts differ from the crater-forming impacts in that the entire energy of a meteoroid is released in the atmosphere (not in the ground) and no observable crater is formed. The aerial bursts differ from meteor events in that they strongly affect the Earth surface. The radiation emitted by a fireball can result in fires [6] and even cause melting of a ground surface [7]; the shock wave from “the air explosion” can lead to mass destructions. The Tunguska catastrophe of 1908 is an example of such an aerial burst [8]. Wasson and Boslough [5] suggested that aerial bursts with considerably higher energy release appear when meteoroids with a rather low density (of cometary origin) enter the atmosphere at small angles to the horizon. This idea was supported by numerical simulations [9].

The aerial bursts have not been sufficiently studied yet, because they are considerably less frequent than typical meteor phenomena and do not leave such well observable and long-lived structures as craters. However, the aerial bursts could play a specific role in the Earth’s history. In particular, Wasson [7] suggested that aerial bursts could lead to the formation of layered tektites [10] and Libyan Desert glass [11]; that is, they could leave their mark in the geologic history of the Earth. In addition, Kovalev et al. [12] noted that the impacts of bodies about 100 m in size, which produce the aerial bursts, are most hazardous for the human civilization. They can cause regional catastrophes and global destructions of telecommunication systems, and, on the other hand, they occur rather frequently, that is, in time significant for human history.

The first simulations of aerial bursts induced by cometary-like impacts [9] have shown that several typical stages can be distinguished in the evolution of a projectile: deformation under aerodynamic loading, progressive disruption due to development of hydrodynamic instabilities, evaporation of fragments and formation of gaseous air-vapor jet, deceleration of the jet and formation of a fireball, rising of the fireball to the upper atmosphere. In this scenario two possible types of aerial bursts are discriminated: Tunguska-like phenomena (high altitude aerial bursts) and surface aerial bursts. In the first, Tunguska-like phenomena, the gaseous jet decelerates at some altitude and a resulting fireball (not touching the ground surface) rises due to buoyancy. In the surface aerial bursts the gaseous jet strikes the ground surface, however, no craters and shock-induced modification of target material are produced because of low bulk density of the jet. If the debris jet strikes the surface before total evaporation of solid fragments it can produce a crater. Such impacts are not included into the class of aerial bursts.

The purpose of this study was to estimate a possible range of impact angles and projectile sizes, at which the surface aerial bursts both by comets and asteroids are produced.

We used the numerical method described in [13, 9], the tabular equations of state and photon path lengths for air [14, 15], vapor of cometary material [16], and vapor of H chondrites [17]. Impact velocities were 15 and 20 km/s for asteroids and 50 km/s for comets.

First of all our simulations have shown that impacts of both stony and comet-like meteoroids with diameters of about 100 m result in the appearance of aerial bursts: the meteoroid material is completely evaporated before being decelerated, and the entire energy is released in the atmosphere. The two types of aerial bursts are also possible for asteroidal impacts: surface (when the fireball touches the Earth’s surface) and high-altitude (when the fireball does not reach the surface) aerial bursts. No crater is formed in both cases. A typical pattern of interaction between a stony asteroid and the Earth’s atmosphere is shown in Fig. 1.
Fig. 1. The destruction of a stony meteoroid with a diameter of 60 m falling at a velocity of 20 km/s at an angle of 45°. The distributions of density (decimal logarithm of density in g/cm³) are shown at different heights. The distances along the trajectory are given on the vertical axis. The brown line indicates the boundary between the meteoroid vapors and the air.

Fig. 2 summarizes the results for cometary (right plate) and asteroidal (left plate) impacts, it shows what type of impacts is realized for different projectile sizes and trajectory angles. One can see that the impact angle is a very important parameter. Solid fragments of cometary meteoroids with initial diameter exceeding 70 m reach the ground in a vertical impact whereas a 1000-m-diameter comet is totally burnt away in the atmosphere in a very oblique 5 degree impact. The violet ellipse shows probable parameters of a Tunguska projectile. Our simulations show that 30 to 45 degree oblique impacts of both a 50 to 60-m-diameter stony meteoroid and a 80 to 100-m-diameter cometary meteoroid could produce effects similar to those observed in the 1908 Tunguska event.

Main conclusions:
- Aerial bursts are produced by comets and asteroids with sizes ranging from tens of meters to about one kilometer (energies from 10 Mt to 100 Gt of TNT equivalents).
- Aerial bursts are more frequent in the Earth’s history than crater forming impacts (they occur on average once in 100 to 1,000,000 years depending on the energy).
- The Tunguska impact is an example of a low energy aerial burst, produced by a 50- to 100-m-diameter comet or asteroid.

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