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The Chelyabinsk event

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Abstract. On February 15, 2013, 3:20 UT, an asteroid of the size of about 19 meters and mass of 12,000 metric tons entered the Earth's atmosphere unexpectedly near the border of Kazakhstan and Russia. It was the largest confirmed Earth impactor since the Tunguska event in 1908. The body moved approximately westwards with a speed of 19 km s^{-1}, on a trajectory inclined 18 degrees to the surface, creating a fireball of steadily increasing brightness. Eleven seconds after the first sightings, the fireball reached its maximum brightness. At that point, it was located less than 40 km south from Chelyabinsk, a Russian city of population more than one million, at an altitude of 30 km. For people directly underneath, the fireball was 30 times brighter than the Sun. The cosmic body disrupted into fragments; the largest of them was visible for another five seconds before it disappeared at an altitude of 12.5 km, when it was decelerated to 3 km s^{-1}. Fifty six second later, that $\sim$ 600 kg fragment landed in Lake Chebarkul and created a 8 m wide hole in the ice. Small meteorites landed in an area 80 km long and several km wide and caused no damage. The meteorites were classified as LL ordinary chondrites and were interesting by the presence of two phases, light and dark. More material remained, however, in the atmosphere forming a dust trail up to 2 km wide and extending along the fireball trajectory from altitude 18 to 70 km. The dust then circled the Earth within few days and formed a ring around the northern hemisphere. In Chelyabinsk and its surroundings a very strong blast wave arrived 90 – 150 s after the fireball passage (depending on location). The wave was produced by the supersonic flight of the body and broke $\sim$ 10% of windows in Chelyabinsk ($\sim$ 40% of buildings were affected). More than 1600 people were injured, mostly from broken glass. The whole event was well documented by video cameras, seismic and infrasonic records, and satellite observations. The total energy was 500 kT TNT (2×10^{15} J).

Keywords. Meteors, Meteoroids, Asteroids

1. Introduction

It is now widely acknowledged that impacts of cosmic bodies (asteroids and comets) played important role in the history of Earth's life. The most significant impacts, of multikilometer bodies, occur only on geological timescales. The largest impact in modern history was the Tunguska event in Siberia on June 30, 1908 (Vasilyev 1998). The asteroid of a size of about 50 meters exploded 5 – 10 km above the surface and its radiation ignited the forest beneath. The blast wave arrived somewhat later, ceased the fire but flattened the forest on an area of 2150 km^2. The total energy of the event was estimated about 15 MT TNT (1 kT TNT = 4.184×10^{12} J). For comparison, the larges thermonuclear test ever conducted (in the USSR in 1961) had an energy of 50 MT TNT, while the Hiroshima bomb had only 15 kT TNT. More recently detected impacts, such as those near Marshall Islands in 1994 (McCord *et al.* 1995) and near Sulawesi, Indonesia, in 2009 (Silber *et al.* 2011) had an energy of the order of tens of kilotons. There was, nevertheless, one unconfirmed event of the energy of 1.5 MT TNT over Indian Ocean in 1963 (Silber *et al.* 2009).

On February 15, 2013, the citizens of the Russian city Chelyabinsk of more than one

Table 1. Energy estimates from various types of data.

Method	Energy (kt TNT)	Reference
Seismic	430	Brown *et al.* (2013)
Infrasound	600	"
US government sensors	530	"
Video-derived light curve	> 470	"
Infrasound	570	Popova *et al.* (2013)

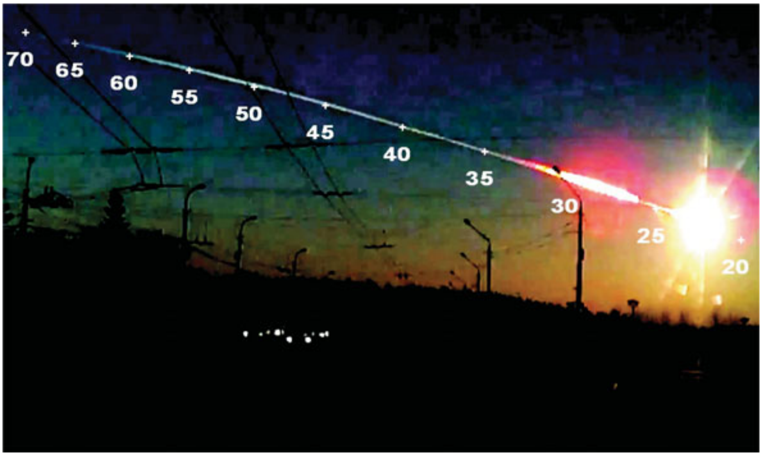

Figure 1. The bolide and fresh dust trail as seen from north. Frame from video taken by A. Ivanov in Kamensk-Uralskyi. The numbers are altitudes in km above ground.

million of inhabitants and the wide surroundings were surprised by bright bolide on the clear morning sky (Fig. 1). Although two small impactors had been discovered (by chance) in space the day before their impacts (Jenniskens *et al.* 2009; Chesley *et al.* 2015), the much larger Chelyabinsk impact came as a surprise. In fact, there was no chance to discover the impactor since it came from the direction close to the Sun (Borovička *et al.* 2013). The atmospheric entry was well documented and we can reconstruct in much more detail what happened than in previous cases. More than 400 casual video records of the bolide, from dashboard cameras in cars, security cameras, and traffic cameras, were posted on the Internet (Borovička *et al.* 2015). Additional hundreds of videos showed the bolide light, dust trail in the atmosphere, or the damage caused by the blast wave. The arrival of the blast wave and secondary sonic booms were recorded in the sound tracks of the videos. Further data came from seismic records and infrasonic records from around the world. The dust trail was imaged from the orbit by meteorological satellites (Proud 2013; Miller *et al.* 2013), see Fig. 2. The US Government sensors also recorded the event. Finally, the recovered meteorites were analyzed.

2. The results

The results of the analyses of various data have been already published in a number of papers, although some more detailed studies are still underway. The estimates of the total energy of the whole event obtained by various methods by different authors are summarized in Table 1. There is good agreement of 500 ± 100 kT TNT. The bolide trajectory was computed from calibrated videos by Borovička *et al.* (2013) and Popova *et al.* (2013) and are also in good agreement. Other computations found in the literature

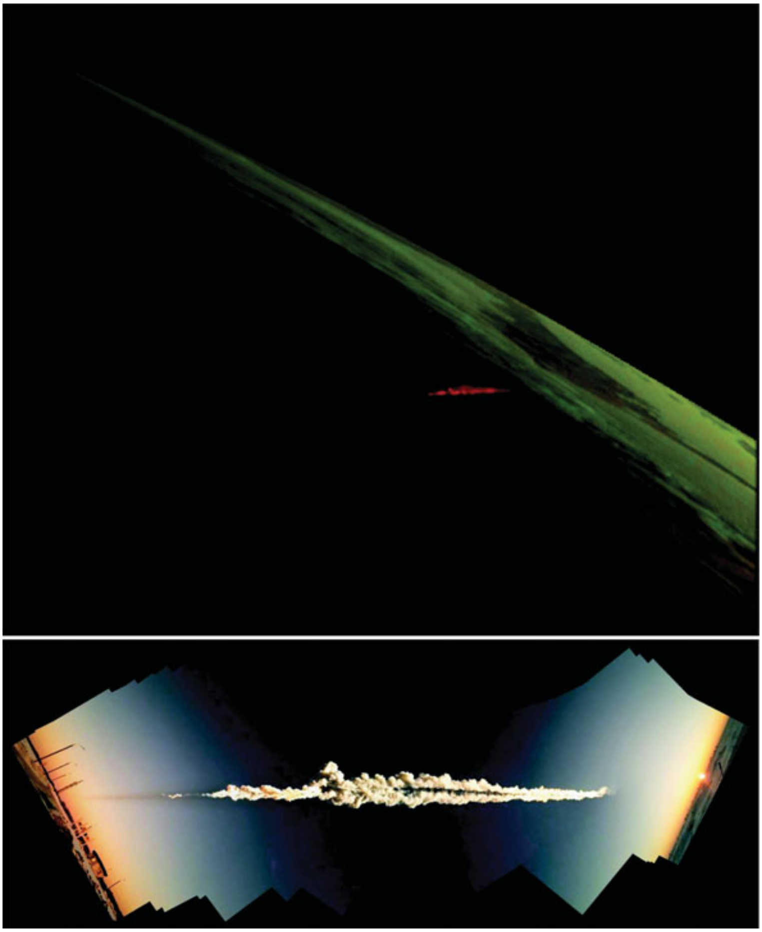

Figure 2. Dust trail from space and from ground. The upper image was taken by MSG2 satellite from geostationary orbit. Combination of visible and infrared channel. Courtesy Eumetsat and CHMI (Z. Charvát). The lower image was composed by L. Shrbený from video taken by A. Vazhenin in Borisovka, where the trail was seen directly overhead and was illuminated by the rising Sun (on the right).

are less reliable. Borovička *et al.* (2013) gave the observed height span 95.1 – 12.6 km, the slope of the trajectory (272 km long) relatively to the horizontal 18.5° at the beginning and 17° at the end (the slope changes primarily due to Earth's curvature, although the trajectory itself was also not straight), the initial velocity 19.03 ± 0.13 km s^{-1}, terminal velocity 3.2 km s^{-1}, and bolide duration 17 seconds.

Combining the known trajectory with the arrival times of the blast wave at various sites, it was proven that the blast wave causing damage was cylindrical not spherical. The wave originated at various heights between 25 – 35 km, not in a single point (Brown *et al.* 2013). It was therefore produced by the supersonic flight of the fragmenting asteroid. Secondary, weaker shocks after the main arrival were spherical waves from various fragmentation points. The region of damage extended perpendicularly from the part of the trajectory, where most energy was deposited (Popova *et al.* 2013). According to Popova *et al.* (2013), windows of 7,230 buildings were affected. Brown *et al.* (2013) examined more than 5000 windows in the city of Chelyabinsk and found that nearly 10% of them broke due to initial shock and 40% of buildings were affected. The window glass velocity

Figure 3. The hole in the ice of Lake Chebarkul caused by the impact of the largest fragment, the largest fragment displayed in Chelyabinsk museum, the collapsed roof and wall of the Chelyabinsk zinc plant, and windows in Chelyabinsk destroyed by the blast wave.

was measured to be 7 – 9 m s^{-1}. The roof one building collapsed (Fig. 3). The pressure was a few percent of atmospheric pressure. Popova *et al.* (2013) reported that 1,613 people asked for medical assistance at hospitals, 112 people were hospitalized, 2 in serious condition. There were, fortunately, no fatalities. Most injuries were from broken glass. Other inconveniences reported by the people were heat, sunburn, painful eyes, temporal deafness, and stress. No significant damage or injuries was caused by falling meteorites.

From the known energy and velocity, the mass of the impacting asteroid was found to be 12,000 kg. Assuming that the density of the meteorites (3300 kg m^{-3}) was valid for the whole body gives the asteroid equivalent diameter 19 ± 2 m. The asteroid severely fragmented in the atmosphere. The fragmentation was modeled by Borovička *et al.* (2013) using the observed light curve (total bolide brightness as a function of time), times of arrivals of secondary sonic booms, and deceleration toward the end of trajectory. Fresh dust trail images were also considered. It was found that intensive dust release (from near-surface) started at height about 70 km. The first fragmentation occurred at 45 km, where 1% of mass was lost. Large scale disruption with 95% mass loss occurred at heights 39 – 30 km. By 29 km the asteroid was fragmented into 10 – 20 boulders of sizes 1 – 3 m. These boulders then broke again at 26 – 22 km. Only one large (~ 0.7 m) fragment survived and landed in Lake Chebarkul (Fig. 3), from where it was lifted up 8 months later (Popova *et al.* 2013).

We can compare the dynamic pressure acting at the fragmentations ($p = \rho v^2$, where ρ is atmospheric density and v is velocity) with the typical tensile strength of meteorites, which is about 50 MPa (Popova *et al.* 2011). The first fragmentation occurred at 0.5 MPa, severe destruction at 1 – 5 MPa, and secondary fragmentation of boulders at 10 – 18 MPa. The maximum pressure encountered by the largest surviving fragment was 15 MPa. The bulk strength of few megapascals is obviously much lower than the strength

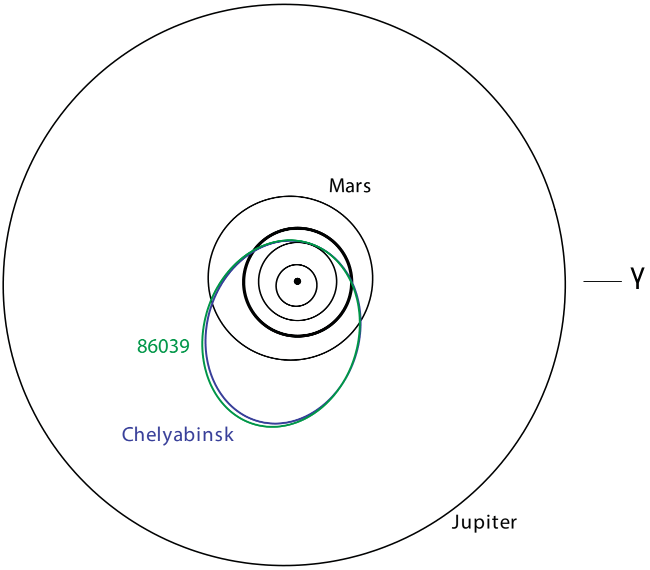

Figure 4. Orbits of Chelyabinsk and asteroid 86039 (1999 NC43).

of meteoritic material but is similar to other meteoroids (Popova *et al.* 2011). The low strength was probably caused by internal cracks from previous collisions in interplanetary space. The parts with strength larger than 10 MPa represented only few percent of the body.

At least 1923 meteorites recovered in a strewn field 80 km long and 7 km wide (Badyukov *et al.* 2014). Most of them very small (mass $\sim$ 1 g). More than 625 kg of meteoritic material was found in Lake Chebarkul (Popova *et al.* 2014). A 24.3 kg fragment was found near Travniki following the prediction of Borovička *et al.* (2013). Other cataloged meteorites have masses 0.04 g – 3.4 kg and total mass 94 kg. Total fallen mass was estimated to 4,000 – 10,000 kg. i.e. only 0.03 – 0.08% of the initial mass (Popova *et al.* 2014).

The meteorites were classified as LL type ordinary chondrite breccia (Kohout *et al.* 2014). LL is a common type of meteorite (represents 9% of all falls). However, two lithologies (light and dark) are present, together with impact melt. All three phases have identical composition. The dark lithology was produced by shock-darkening (Kohout *et al.* 2014; Reddy *et al.* 2014; Richter *et al.* 2015). Its reflectance spectrum can mimic carbonaceous material. The cosmic ray exposure age was measured to be 1.2 Myr, one of the lowest among LL chondrites (Popova *et al.* 2013; Povinec *et al.* 2015).

The dust trail left in the atmosphere was mostly formed by micron sized dust. It represents unablated residuals of tiny fragments. Total mass of the dust may be 25% of the initial mass (Popova *et al.* 2013). Within few days after the event, the dust circled the globe forming a optically thin dust ring around the northern hemisphere (Gorkavyi *et al.* 2013). The dust remained detectable in the atmosphere for three months (Rieger *et al.* 2014).

The pre-impact orbit of the asteroid was found to be very similar to that of asteroid 86039 (1999 NC43) with diameter of about 2 km (Borovička *et al.* 2013). Although there is only $\sim$ 1:10,000 chance that the proximity of Chelyabinsk orbit (Fig. 2) to an asteroid of this size is due purely to chance, spectral comparison did not confirm genetic relation

(Reddy *et al.* 2015). Detailed analysis of the reflectance spectrum of 1999 NC43 showed that it is of type L rather than LL.

The statistics of large bolides (Brown *et al.* 2013) and asteroid discoveries (Harris & D'Abramo 2015) now agree better than in the past and suggest that the impacts of Chelyabinsk size occur globally once per 40 ± 20 years on average.

3. Summary

The Chelyabinsk event was the first asteroid disaster in (at least modern) history. The damage was from the blast wave. If the body were stronger and penetrated deeper intact, the blast wave would be more damaging. In any case Chelyabinsk demonstrated that 20-m asteroids are dangerous and that asteroids of this size are more numerous than was thought several years ago. The new survey telescopes like ATLAS (Tonry 2011) and LSST (Jones *et al.* 2009) can provide advance warning if the impactor comes from the night side. Day side can be covered only from space.

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