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LETTER

Letter to the Editor

On the airburst of large meteoroids in the Earth's atmosphere

The Lugo bolide: reanalysis of a case study

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Abstract. On January 19, 1993, a very bright bolide (peak magnitude -23) crossed the sky of Northern Italy, ending with an explosion approximately over the town of Lugo (Emilia Romagna, Italy). The explosion (14 kton of energy) generated shock waves which were recorded by six local seismic stations. A reanalysis of the available data leads us to the hypothesis that the meteoroid was a porous carbonaceous chondrite, somehow similar in constitution to the asteroid 253 Mathilde.

Key words: meteors, meteoroids – minor planets

1. Introduction

The atmospheric interaction of large meteoroids provides our primary tool to characterize their population, physical and chemical properties, and dynamical evolution. In turn, this can lead to a better understanding of the diverse populations of small bodies of the Solar System. Currently, our knowledge is still quite limited, although, especially after the impact of comet D/Shoemaker–Levy 9 on Jupiter, the research efforts in this field have been intensified. In particular, in 1994 the US Department of Defense made of public domain its records on energetic bolides over a time span of about twenty years (Tagliaferri et al. 1994). These data indicate that, from 1975 to 1992, there were 136 airbursts of energy greater than 1 kton, but the real number was probably at least 10 times higher, because the satellite system does not cover the entire Earth surface.

Both data and theories are required to assess the impact hazard and to understand the very bright bolides. From this point of view, the Lugo bolide is a very interesting event, because the airburst was detected by several seismic stations. The corresponding data allow us to characterize the meteoroid and to draw some tentative inferences about its nature and origin. We have carried out a reanalysis of this event and we found that the data are most consistent with the hypothesis that the involved meteoroid was a porous carbonaceous chondrite, somehow similar to the asteroid 253 Mathilde.

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2. The Lugo bolide

On 1993 January 19 at 00:33:29 UT a large meteoroid entered the atmosphere approximately over the town of Lugo, in Emilia Romagna, Italy. The impact was recorded by the National Research Council (CNR) forward–scatter meteor radar and by six seismic stations, three belonging to the Microseismic Network of Ferrara (Pontisette, Cà Fornasina, Fiorile d'Albero) and the others to the National Institute of Geophysics (Barisano, Santa Sofia, Poggio Sodo). The event was also observed by several eyewitnesses, as it lit an extremely large area (almost all of Italy), and they reported a visual magnitude in the range -22 to -25. Preliminary calculations were carried out based on the eyewitness reports, although they were fragmentary and sometimes contradictory (Cevolani et al. 1993, Korlević 1993). Only at a later time we found seismic data which enabled us to infer the location of the explosion (Cevolani et al. 1994). This analysis indicated that a meteoroid of initial radius in the range $1.5 \div 3$ m impacted the Earth atmosphere at a velocity of about 26 km/s, with an inclination of the trajectory to the horizon of $8^\circ \div 20^\circ$. By means of the seismic data, it was possible to calculate the height (30 ± 3 km), latitude ($44^\circ.48 \pm 0^\circ.01$ N) and longitude ($11^\circ.91 \pm 0^\circ.01$ E) of the explosion.

3. The reanalysis: aerodynamics

Here, we will assume that the only reliable data are those recorded by the seismic stations, which in general are a very useful tool for understanding this kind of airburst (e.g. Ben-Menahem 1975). Therefore, we assume as valid the height, latitude and longitude of the explosion only, i.e. those data calculated from seismic data (Cevolani et al. 1994).

The aerodynamics of large meteoroid/small asteroid impacts has been studied by several authors, sometimes with special reference to the 1908 Tunguska explosion (e.g. Ceplecha and McCrosky 1976, Ceplecha et al. 1993, Chyba et al. 1993, Hills and Goda 1993, Lyne et al. 1996). Although the details may vary, there is a consensus that a 30 km explosion height is typical for a carbonaceous chondrite or a cometary body. In the theory of Hills and Goda (1993) the height of first fragmenta-

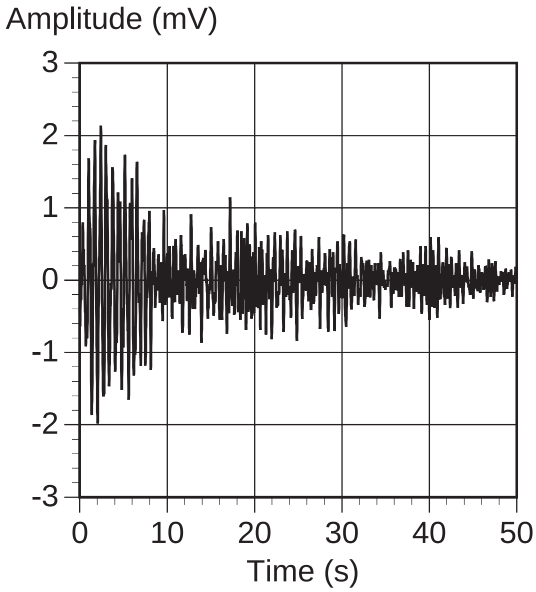

Fig. 1. Seismic plot recorded at the Pontisette station. Time starts at 00:36:37.3 UT. Further plots of this type can be found in Cevolani et al. (1994).

tion is calculated comparing the stagnation pressure in front of the meteoroid ($P_{max} = \rho_0 V_e^2$) to the mechanical strength S of the cosmic body. We rearrange the formula to evaluate the meteoroid speed (V_e):

$$V_e = \sqrt{\frac{S}{\rho_0} \exp\left[\frac{h_e}{H}\right]} \tag{1}$$

where ρ_0 is the atmospheric density at the sea level [kg/m^3], h_e is the height of first fragmentation [km] and H is the atmospheric scale height (about 8 km). For the strength, we assume $S = 10^7$ Pa, that is an intermediate value between those appropriate for carbonaceous chondrites and for cometary bodies. We obtain $V_e = 18 \pm 3$ km/s, that is a value much lower than that derived previously (about 26 km/s).

Observing the seismic plots (e.g. Fig. 1), we can conclude that there was a single explosion (for a comparison with nuclear explosions, see Pierce et al. 1971). There is no evidence of multiple explosions, as it should occur during multiple fragmentation. Thus, for the Lugo bolide, Eq. (1) can be used by assuming that the first fragmentation corresponded to the airburst.

In order to calculate the flight path angle, we have to solve two equations:

$$\frac{dh}{dt} = V \cdot \sin\theta\,, \tag{2}$$

$$\frac{d\theta}{dt} = -\frac{\cos\theta}{V}\left(g - \frac{V^2}{R+h}\right)\,, \tag{3}$$

where g is the gravity acceleration [m/s^2], R is the Earth's radius (we assume $R = 6367$ km, for about 45° latitude), and θ is the flight path angle, measured from the horizontal. We assume that the meteoroid lift can be neglected. For the Tunguska cosmic body, Chyba et al. (1993) assumed a lift value of 10^{-3} and found that its influence on the results of these calculations is only about 1%. With all these assumptions, we obtain that the flight path angle during the final part of the atmospheric trajectory was $\theta = 5.0^\circ \pm 0.3^\circ$. Again, we have some disagreement with the previous results ($8^\circ \div 20^\circ$). This is probably due to the uncertainty of visual observations in these conditions: for such an event the surprise can reduce significantly the skills and reliability of eyewitnesses.

4. The reanalysis: explosion energy

To obtain an estimate of the explosion energy, we can use the relationship for the maximum velocity of displacement of the solid rocks, obtained from studies on underground nuclear explosions (Adushkin and Nemchinov 1994). We rearrange their equation in order to calculate the energy, when the distance and the displacement velocity are known:

$$E = k \cdot D^3 \left(\frac{v}{240}\right)^{12/7}\,, \tag{4}$$

where E is the explosion energy in kton of TNT; D is the distance of the sensor from explosion [km]; v is the displacement velocity [mm/s]. This formula is valid for $D < 100$ km: in our case, seismic stations were located at distances smaller than 70 km. The coupling coefficient k is introduced to take into account that, in order to produce rock displacements, an airburst is less effective than an underground nuclear explosion (at least by a factor 100). Moreover, there is a difference in the effective energy, because the explosion of a meteoroid in the atmosphere does not involve nuclear fission, and this contributes about another factor 10. Finally, there is some increase of the wave amplitude with the height of burst up to 40 km (Pierce et al. 1971), which typically exceeds a factor 2; we assume a power increase by a factor 5. Overall, we estimate $k = 100 \cdot 10 \cdot \frac{1}{5} = 200$.

We have data from six seismic stations (for a complete set of plots and other information, see Cevolani et al. 1994), but transfer functions are available only for the three stations belonging to the Microseismic Network of Ferrara. We have performed a Fourier analysis of the waveform and found a peak at 1.4 Hz, for both Pontisette and Cà Fornasina, corresponding to the airburst (see Figs. 2 and 3). We have not taken into account data from the Fiorile d'Albero station, because they show a strong background noise overlapping the shock wave and preventing a reliable Fourier analysis.

The transfer function has a nominal value of 175 mV·s/mm for all stations and for frequencies greater than 2 Hz. Below the cutoff frequency, the transfer function is drastically reduced, down to a value of 10 mV·s/mm for 0.5 Hz. For a frequency of 1.4 Hz, we have a transduction factor of 52 mV·s/mm. The final results of our calculations for the explosion energy from the seismic data with Eq. (4) are shown in Table 1.

We consider a mean value of 14 ± 2 kton, that is $(5.9\pm0.8)\times 10^{13}$ J. It is worth noting that we might have obtained more accurate values, but the saturation of the Barisano sensor introduced an error of 9% in the burst height calculations (Cevolani et al. 1994), which propagates to our results. On the other hand, had

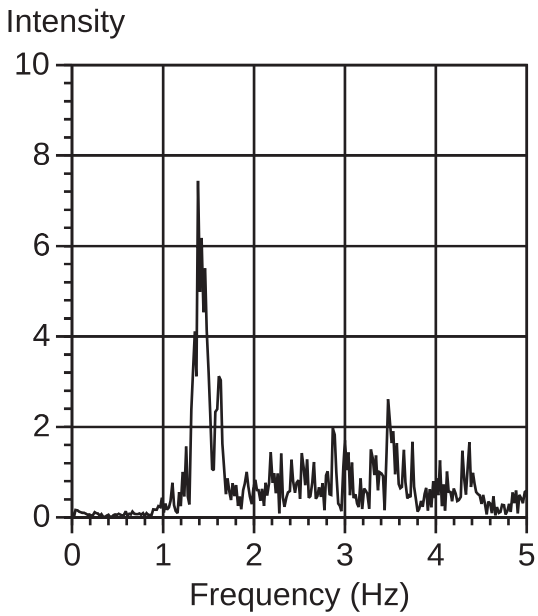

Fig. 2. Fourier analysis of the Pontisette seismic plot.

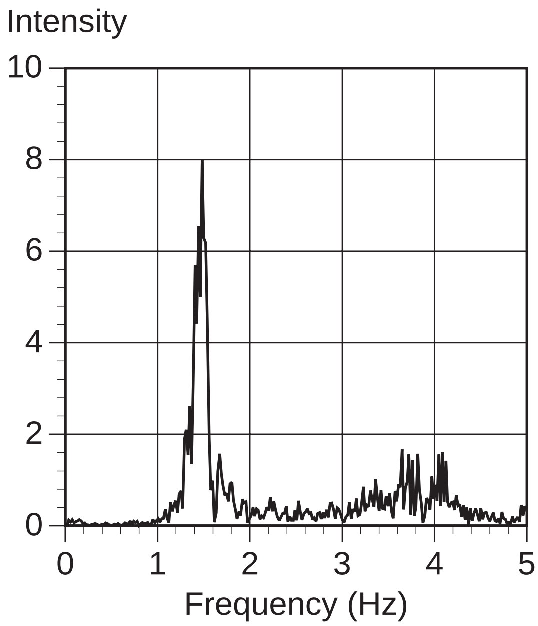

Fig. 3. Fourier analysis of the Cà Fornasina seismic plot.

Table 1. Explosion energy calculated from the seismic data.

Station	D [km]	v [μm/s]	E [kton]
Pontisette	59 ± 3	41.040 ± 0.002	14 ± 2
Cà Fornasina	63 ± 3	35.369 ± 0.002	13 ± 2

we not considered the Barisano data, the available data would have been insufficient for a meaningful analysis.

When a cometary body or a carbonaceous chondrite enters the atmosphere, almost all the kinetic energy is released in the explosion. Then we can calculate the meteoroid mass, taking into account that during the path preceding the explosion the cosmic body undergoes a limited mass loss:

$$m = \frac{2E}{V^2} = (4 \pm 1) \cdot 10^5 \text{ [kg]} . \qquad (5)$$

In order to calculate the visual magnitude of the airburst, we have to solve the equation:

$$L = -\tau \frac{dm}{dt} \frac{V^2}{2} , \qquad (6)$$

where τ is the dimensionless coefficient for the meteor luminous efficiency. This coefficient mainly depends on the meteoroid speed and is quite uncertain (Ceplecha and McCrosky 1976). Some authors think that for very bright bolides τ ranges from 10 to 30% (Brown et al. 1996, McCord et al., 1995). Others assume τ values between 1.5 and 6.1% (Borovička and Spurný 1996, Ceplecha 1996). Here we assume $\tau = 4.5\%$.

Moreover, we assume that the meteoroid dissipated almost all of its energy within a scale height. Then, solving Eq. (2) for the time during which the meteoroid exploded, we obtain $t = 5.1 \pm 0.8$ s. The corresponding value for the airburst luminosity is $(5 \pm 1) \cdot 10^{11}$ J/s. In order to express the luminosity in terms of absolute magnitude (i.e., the magnitude as observed at a 100 km distance), we can use the equation:

$$M = -2.5 \cdot (\log_{10} L - 2.63) , \qquad (7)$$

where we have rearranged the classical relationship in order to use the SI unit system. From Eq. (7) we obtain $M = -22.7 \pm 0.5$, a value consistent with visual observations ($-22 \div -25$). We stress the importance of the coefficient τ: assuming a value of 10%, as suggested by McCord et al.(1995), we would obtain $M \simeq -24$.

5. Further results and discussion

It is also interesting to check how the results are sensitive to the assumed value of the strength S. If we take $S = 10^6$ Pa, that is typical for cometary bodies, we end up with a cosmic body with a speed of about 6 km/s and an inclination of $2°$. The mass would be about 3×10^6 kg and the absolute visual magnitude -21. The airburst would have been 31 s long. These values appear unlikely. Note that a final velocity of 6 km/s is very close to 4 km/s, which Ceplecha (1994) indicated as necessary to have a meteorite fall. But for Lugo no meteorite was recovered.

We can summarize some features of the Lugo bolide: it had a grazing trajectory in the atmosphere, it was probably a carbonaceous chondrite, but it exploded at a height higher than usual and with a single airburst, without fragmentations. The recent discovery by the NEAR probe of a carbonaceous asteroid (253 Mathilde) with a very low density (about 1300 kg/m^3) suggests the existence of porous bodies (i.e. bodies with internal cavities) among asteroids (Yeomans et al. 1997). If we assume that the Lugo bolide was a porous carbonaceous chondrite, we have a body which was probably stronger than a cometary fragment, but which could explode at a higher altitude than those typical for stony objects, because of its porosity. It is very likely that

LETTER

Table 2. Summary on the properties of the Lugo bolide.

Apparition time (UT)	1993 01 19 00:33:29 ± 1 s
Latitude of airburst[a]	$44.48° \pm 0.01°$ N
Longitude of airburst[a]	$11.91° \pm 0.01°$ E
Airburst height[a]	30 ± 3 km
Explosion Energy	14 ± 2 kton
Mass	$(4 \pm 1) \cdot 10^5$ kg
Abs. Visual Magnitude	-22.7 ± 0.5
Velocity	18 ± 3 km/s
Inclination[b]	$5.0° \pm 0.3°$
Path azimuth[a,c]	$146.5° \pm 0.5°$

[a] Calculated in Cevolani et al. (1994).
[b] Over the horizon.
[c] Clockwise from North.

porosity increases the burst efficiency: when ablation removes the surface of the body, cavities may appear which increase the aerobraking and generate a sudden deceleration. The kinetic energy then is rapidly transformed into heat, so that the body bursts within a scale height. This is consistent with a single explosion, without multiple fragmentation, as indicated by seismic plots (see Fig. 1).

6. Conclusions

The Lugo bolide has been reanalysed by taking into account only the data recorded by seismic stations. We summarize the main inferred properties of the bolide in the following Table 2.

We are now carrying out calculations on the orbit and the dynamical evolution this bolide, whose results will be available soon. However, from the analysis described here it appears likely that the meteoroid was a porous carbonaceous chondrite, somehow similar in constitution to the asteroid 253 Mathilde. The porosity would have increased the braking and as a consequence the airburst occurred at a height higher than for a compact carbonaceous chondrite object.

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