The impact hazard from small asteroids: current problems and open questions

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Abstract

The current philosophy of impact hazard considers the danger from small asteroids negligible. However, several facts claim for a revision of this philosophy. In this paper, some of these facts are discussed. It is worth noting that while the impact frequency of Tunguska–like objects seems to be higher than previously estimated, the atmospheric fragmentation is more efficient than commonly thought. Indeed, data recorded from airbursts show that small asteroids breakup at dynamical pressures lower than their mechanical strength. This means that theoretical models are inconsistent with observations and new models and data are required in order to understand the phenomena.

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1 Introduction

The interest in the impact of interplanetary bodies with planets, particularly with Earth, has been increased significantly during the last few years because of several events such as the fall of the D/Shoemaker–Levy 9 into Jupiter’s atmosphere.

Particular attention was given to the detection of kilometre–sized objects, which pose a severe threat to the Earth. In recent years, this has been
emphasized by several authors with differing points of view (e.g. Aduskhin and Nemtchinov 1994, Chapman and Morrison 1994, Toon et al. 1997). The reason is quite simple, as written by Clark Chapman (1996): the impact of such an object has non-zero probability of creating a global ecological catastrophe within our lifetime.

Larger objects (tens of kilometres) can cause an extinction level event. The consequent “asteroidal winter”, deriving from a strong injection of dust in the atmosphere, is quite similar to the nuclear winter, radioactive consequences apart. It would cause the onset of environmental conditions whose main features are: a very long period of darkness and reduced global temperature, something similar to the polar winter on a world wide scale (Cockell and Stokes 1999).

Even though I understand and respect these opinions, I think that we cannot neglect small bodies at all. There are two main reasons: first, the fragmentation of asteroids in the Earth’s atmosphere is not well known. Observations of small asteroids (up to tens of metres) show that the fragmentation occurs when the dynamical pressure is lower than the mechanical strength, and there is no reason to suppose that larger bodies behave differently. Therefore, airburst can give us data to test theories for fragmentation, which are also valid for larger bodies.

The second reason is that, although the damage caused by Tunguska–like can be defined as “local”, it is not negligible. Specifically, there are several scientists, such as J. Lewis, M. Paine, S.P. Worden and B.J. Peiser (see debates in the Cambridge Conference Net), suggesting that small asteroids might be even more dangerous than larger bodies.

Moreover, David Jewitt (2000), after the paper by Rabinowitz et al. (2000) where authors strongly reduced the number of NEO larger than 1 km, suggested that it is time to set up a more ambitious NEO survey, including small objects.

The present paper does not present any new theory or observation, but it review some points that are not present in previous analyses and studies. The purpose of this paper is to strengthen studies on small objects simply because our knowledge is very poor. The paper is divided into two parts: in the Section 2, I add some notes to the debate on the danger from small asteroids. In the Sects. 3 and 4, I present the evidence that the fragmentation of small asteroids in the Earth’s atmosphere is still an open problem.
2 Tunguska–like events

Small objects, of the order of tens or hundreds of metres, can cause severe local damages. The best known event of this kind is the Tunguska event of 30 June 1908, which resulted in the devastation of an area of $2150 \pm 25 \text{ km}^2$ and the destruction of more than 60 million trees (for a review, see Vasilyev 1998). Still today there is a wide debate all over the world about the nature of the cosmic body which caused that disaster. Just last July an Italian scientific expedition, Tunguska99, went to Siberia to collect data and samples (Longo et al. 1999).

Chapman and Morrison (1994) considered Tunguska–like events as a negligible threat. They could be right, considering the substantial uncertainties in these studies, but they underestimate some values. Although they proposed data with large error bars, the question is: where do we have to center these bars?

Let us analyse the assumptions of Chapman and Morrison: first of all, they consider that the area destroyed in Tunguska (i.e. the area where the shock wave was sufficient to fell trees) was about $1000 \text{ km}^2$. This value is somehow larger than the area where the peak overpressure reached the value of 4 psi (27560 Pa), sufficient to destroy normal buildings (according to the formula quoted by Chapman and Morrison the area of 4 psi is about 740 km$^2$, using a yield of 20 Mton).

There are two main objections to this hypothesis: firstly, the measured value of the area with fallen trees is more than double (see above; Vasilyev 1998). In addition to this, it is worth noting that an overpressure of 2 psi produces wind of 30 m/s, which is sufficient to cause severe damages to wood structures. In addition to this, debris flying at such speed is a threat to life (Toon et al. 1997).

Therefore, a reasonable value of human beings risking death during a Tunguska–like event is $10^4$, rather than $7 \times 10^3$ as indicated by Chapman and Morrison. The above value has been calculated by using the formula in Adushkin and Nemtchinov (1994) and assuming an explosion energy of 12.5 Mton (Ben–Menahem 1975).

Chapman and Morrison (1994) correctly note that there is a much greater probability that such an event might occur in an uninhabited part of the world. On the other hand, in the unlikely event of it occurring in a populated city, it would cause a great disaster. For example, in Rome which has a population density of about 2000 people per square kilometre the number of
human beings at risk would be more than 2 millions.

It is also necessary to evaluate the impact frequency of Tunguska–like events. Chapman and Morrison consider a time interval of 250 yr, but several other studies and episodes suggested a lower value. Farinella and Menichella (1998) studied the interplanetary dynamics of Tunguska–sized bodies by means of a numerical model and they found that the impact frequency is 1 per 100 yr. However, in that study, the authors did not take into account the Yarkovsky effect (see Farinella and Vokrouhlický, 1999, and references therein), that can slightly increase the delivery of NEO (Near Earth Objects) toward the Earth.

There are also ground–based and space–based observations that support these conclusions, even though the frequency range can vary greatly. For a 1 Mton explosion, the impact frequency can be once in 17 (ReVelle 1997) or 40 yr (Nemtchinov et al. 1997b), that implies a Tunguska event (12.5 Mton) once in 100 or 366 yr. If we consider an energy of 10 Mton, as calculated by Hunt et al. (1960), we obtain a value of the impact frequency of respectively 88 or 302 yr. In addition to this, Steel (1995) reports two other Tunguska–like event in South America in 1930 and 1935: this strengthens the impact frequency value of one per 100 yr (or less).

Now, if we consider a typical time interval of one Tunguska–like impact per 100 yr and $10^4$ deaths per impact, we obtain 100 death per years throughout the world; this value is no longer negligible in the Chapman and Morrison’s scale (1994).

On the other hand, we would stress the great uncertainty of these values, which are mainly due to the use of empirical relations with scarce data. We are aware that the threat posed by kilometre and multikilometre objects is more dangerous and therefore we must study these objects and methods to avoid a global catastrophe. However, the few points raised in this paper suggest that we must also study Tunguska–like events. In addition to this, it is worth noting that studies about the impact hazard are often based on models of cosmic bodies fragmentation in the Earth’s atmosphere. These models assume that the fragmentation begins when the dynamical pressure in the stagnation point is equal to the mechanical strength of the body. However, as we shall see, this does not occur.
3 The failure of current theories

The calculations of the impact hazard are strongly related to available numerical models for the fragmentation of asteroids/comets in the Earth’s atmosphere. Present models consider that fragmentation begins when the dynamical pressure in front of the cosmic body is equal to the material mechanical strength. However, observations of very bright bolides proves that large meteoroids or small asteroids breakup at dynamical pressures lower than their mechanical strength. Today there is still no explanation for this conundrum. This is of paramount importance, because it allow us to know whether or not an asteroid might reach the Earth’s surface. In addition to this, the atmospheric breakup also effects the crater field formation (Passey and Melosh 1980) or on the area devastated by the airblast. Therefore, it allows us to establish a reliable criterium to assess the impact hazard. All studies shown above are based on models where fragmentation begin when the dynamical pressure is equal to the mechanical strength of the asteroid. But, as we shall see, observations indicate that this is not true.

The interaction of a cosmic body in the Earth’s atmosphere can be divided into two parts, according to the body dimensions. For millimetre to metre sized bodies (meteoroids), the most useful theoretical model is the gross–fragmentation model developed by Ceplecha et al. (1993) and Ceplecha (1999). In this model, there are two basic fragmentation phenomena: continuous fragmentation, which is the main process of the meteoroid ablation, and sudden fragmentation or the discrete fragmentation at a certain point.

For small asteroids another model is used, where the ablation is contained in the form of explosive fragmentation, while at high atmospheric heights it is considered negligible. Several models have been developed: Baldwin and Shaeffer (1971), Grigoryan (1979), Chyba et al. (1993), Hills and Goda (1993), Lyne et al. (1996). A comparative study on models by Grigoryan, Hills and Goda, and Chyba–Thomas-Zahnle was carried out by Bronshten (1995). He notes that the model proposed by Chyba et al. does not take into account fragmentation: therefore, the destruction heights are overestimated (about 10–12 km). Bronshten also concludes that the Grigoryan and Hills–Goda’s models are equivalent.

There is also a class of numerical models, called “hydrocodes” (e.g., CTH, SPH), which were used particularly for the recent impact of Shoemaker–Levy 9 with Jupiter. Specifically, Crawford (1997) uses CTH to simulate the
impact, while M. Warren, J. Salmon, M. Davies and P. Goda used SPH. The latter was only published on the internet and is no longer available.

Despite the particular features of each model, fragmentation is always considered to start when the dynamical pressure $p_0$ in the front of the meteoroid (stagnation point) exceeds the mechanical strength $S$ of the body.

Although direct observations for asteroid impact are not available, it is possible to compare these models with observations of bodies with dimensions of several metres or tens of metres. Indeed, in this range, the gross-fragmentation model overlaps the explosive fragmentation models. As underlined several times by Ceplecha (1994, 1995, 1996b), observations clearly show that meteoroids breakup at dynamical pressures lower (10 times and more) than their mechanical strength. These data are obtained from photographic observation of meteors and the application of the gross-fragmentation model, that can be very precise. According to Ceplecha et al. (1993) it is possible to distinguish five strength categories with an average dynamical pressure of fragmentation (Tab. 1).

| Category | Range of $p_{fr}$ [MPa] | Average $p_{fr}$ [MPa] |
|----------|-------------------------|------------------------|
| a        | $p < 0.14$               | 0.08                   |
| b        | $0.14 \leq p < 0.39$    | 0.25                   |
| c        | $0.39 \leq p < 0.67$    | 0.53                   |
| d        | $0.67 \leq p < 0.97$    | 0.80                   |
| e        | $0.97 \leq p < 1.2$     | 1.10                   |

For continuous fragmentation the results obtained also indicate that the maximum dynamical pressure is below 1.2 MPa, but five exceptions were found: 4 bolides reached 1.5 MPa and one survived up to 5 MPa (Ceplecha et al. 1993).

It is also very important to relate the ablation coefficient $\sigma$ with the fragmentation pressure $p_{fr}$, in order to find a relationship between the meteoroid composition and its resistance to the air flow. To our knowledge, a detailed statistical analysis on this subject does not exist, but in the paper by Ceplecha et al. (1993) we can find a plot made by considering data on 30 bolides (we refer to Fig. 12 in that paper). We note that stony bodies (type I) have a wide range of $p_{fr}$ values. In the case of weak bodies, we can see that there is only one cometary bolide (type IIIA), but this is due
to two factors: firstly, cometary bodies undergo continuous fragmentation, rather than a discrete breakup at certain points. Therefore, it is incorrect to speak about fragmentation pressure; we should use the maximum tolerable pressure. The second reason is that there is a selection effect. Indeed, from statistical studies, Ceplecha et al. (1997) found that a large part of bodies in the size range from 2 to 15 m are weak cometary bodies.

However, a recent paper has shown that statistics from physical properties can lead to different results when compared with statistics from orbital evolution (Foschini et al. 2000). To be more precise, physical parameters prove that, as indicated above, a large part of small near Earth objects are weak cometary bodies, whilst, the analysis of orbital evolution proves a strong asteroidal component.

The reason for the presence of cosmic bodies with very low fragmentation pressure can be explained by the assumption that additional flaws and cracks may be created by collisions in space, even though they do not completely destroy the cosmic body (Baldwin and Shaeffer 1971). Other explanations could be that the asteroid was not homogeneous (see the referee’s comment in Ceplecha et al. 1996) or it had internal voids (Foschini 1998).

These are hypotheses, interesting hypotheses, but all the same none of them are conclusive.

4 Special cases

In addition to data published in the paper by Ceplecha et al. (1993) and Ceplecha (1994) we consider some specific cases of bright bolides. We provide here a short description and we refer for details to the papers quoted.

The Lost City meteorite (January 3, 1970), a chondrite (H), was analysed by several authors (McCrosky et al. 1971, Revelle 1979, Ceplecha 1996a). The recent work by Ceplecha (1996a) is of particular interest, because by taking into account the meteoroid rotation, he succeeds in explaining the atmospheric motion without discrepancies. Obviously, except the dynamical pressure, that in this episode reaches the value of $p_{fr} = 1.5$ MPa, while the mechanical strength of a stony body is about 50 MPa.

In the work by Revelle (1979), it is also possible to find useful data for two other episodes: Příbram (April 7, 1959) and Innisfree (February 6, 1977). In both episodes a meteorite was recovered: respectively ordinary chondrite and L chondrite. Values for $p_{fr}$ of 9.2 MPa and 1.8 MPa respectively were
Table 2: Special episodes.

| Name           | Date       | max $p_{fr}$ | $S$ |
|----------------|------------|--------------|-----|
| Příbram        | Apr 7, 1959| 9.2          | 50  |
| Lost City      | Jan 3, 1970| 1.5          | 50  |
| Šumava         | Dec 4, 1974| 0.14         | 1   |
| Innisfree      | Feb 6, 1977| 1.8          | 10  |
| Space based obs.| Apr 15, 1988| 2.0          | 50  |
| Space based obs.| Oct 1, 1990| 1.5          | 50  |
| Benešov        | May 7, 1991| 0.5          | 10  |
| Peekskill      | Oct 9, 1992| 1.0          | 30  |
| Marshall Isl.  | Feb 1, 1994| 15           | 200 |

obtained in this work.

The Šumava bolide (December 4, 1974) reached −21.5 absolute visual magnitude and was produced by a cometary body. It exhibited several flares during continuous fragmentation, ending at a height of about 60 km. The maximum dynamical pressure was in the range 0.025 – 0.14 MPa, much lower than the mechanical strength of a cometary body, i.e. 1 MPa (Borovička and Spurný 1996).

The Benešov bolide (May 7, 1991) was very atypical and was analysed in detail by Borovička and Spurný (1996) and Borovička et al. (1998a, b). From these studies, results show that it was very probably a stony object which underwent a first fragmentation at high altitudes (50 – 60 km) at dynamical pressures of about 0.1 – 0.5 MPa. However, some compact fragments were disrupted at pressures of 9 MPa (24 km of height).

The fall of the Peekskill meteorite (October 9, 1992) was the first of such events to be recorded by a video camera (Ceplecha et al. 1996). The fireball was brighter than the full moon and 12.4 kg of ordinary chondrite (H6 monomict breccia) were recovered. The availability of a video recording allows us to compute, with relative precision, the evolution of the meteoroid speed and, therefore, the dynamical pressure. It was discovered that the maximum value of $p_{fr}$ was about 0.7 – 1.0 MPa, while the meteorite has an estimated strength close to 30 MPa.

In recent years, space–based infrared sensors detected several bolides all around the world. Nemtchinov et al. (1997) investigated these events by using a radiative–hydrodynamical numerical code. They simulated three bright bolides (April 15, 1988; October 1, 1990; February 1, 1994) and they obtained
respectively these results: stony meteoroid, $p_{fr} = 1.6 - 2.0$ MPa; stony meteoroid, $p_{fr} = 1.5$ MPa; iron meteoroid, $p_{fr} = 10 - 15$ MPa. Concerning the latter, Tagliaferri et al. (1995) reached a slightly different conclusion: stony meteoroid, $p_{fr} = 9$ MPa.

The condition that fragmentation starts when the dynamical pressure reaches the mechanical strength of the meteoroid was imposed by Baldwin and Shaeffer (1971), but it is worth noting that this is a hypothesis. Now we have sufficient, though incomplete, data to claim that this hypothesis has no physical ground and we have to find new conditions for fragmentation.

5 Conclusion

Only in recent decades, and particularly in recent years, the impact hazard has attracted the attention of more and more scientists. Evaluation of impact frequencies and damages are made by means of empirical or semiempirical formulas. However, we are faced with scarce, and often contradictory data. For example, Chapman and Morrison (1994) considered an impact frequency of one Tunguska–like event every 250 yr by using data from lunar craters, ReVelle obtains a higher frequency for the same kind of objects (1 per 100 yr) by considering data from airbursts.

However, the main problem is the fragmentation mechanism, that is still unclear. From observations, it results that fragmentation occurs when the dynamical pressure is lower than the mechanical strength. We do not know whether this is due to any special feature in the hypersonic flow around the body or to any particular matter in the body. Today all that we can say is that current models of fragmentation of small asteroids in the Earth’s atmosphere are not consistent with observations. We require more data and theories to understand the matter better. Airbursts can give us useful data to test theories.

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