PLANETARY DEFENSE: A METEORITE PERSPECTIVE*

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Abstract

Meteorites, and their fall to Earth, have the potential to inform studies of the asteroid impact hazard and of impact mitigation. Meteorites are the rocks that fall on Earth. They come to Earth as asteroids or asteroid fragments. We describe six ways in which they have relevance to planetary defense. (1) Hundreds of meteorite falls have been described in the literature. While eyewitness observations are subjective, at their core there is unique information on which to build and test numerical models of an asteroid's behavior as it passes through the atmosphere. (2) For 16 recovered meteorites, light curves have been obtained which provide quantitative information on meteorite fall and fragmentation. (3) There are about 250 known meteorite craters on Earth and in 11 cases fragments of the meteorite responsible have been recovered. In these cases numerical impact models can utilize the known properties of the projectile. (4) Studies of the meteorites provide information on their preatmospheric size, internal structure, and physical properties (tensile strength, density, porosity, thermal conductivity etc.) which are essential for numerical modelling of the atmospheric behavior of objects coming through the atmosphere. (5) The flow patterns on the fusion crust of the meteorite, and the shape of the recovered meteorite, provides information on orientation and physical behavior during flight. Petrographic changes under the fusion crust provide information on thermal history during the latter stages of flight. (6) The structure and composition of the so-called "gas-rich regolith breccias"

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provide information on the outermost layer of the parent asteroid from which the meteorites came. This information is critical to certain mitigation strategies.

Most meteorite falls are relatively small events, although Chelyabinsk is a recent example of a meteorite fall energetic enough to damage property over a wide area and send over 1200 people to hospital. Crater-forming events are orders of magnitude more energetic and it is significant that all but one of the ten craters with meteorite fragments on Earth were formed by iron meteorites; clearly mechanical strength of the projectile is an important factor in determining atmospheric behavior. However, it is not clear whether a stony meteorite that produced an airburst and a strong pressure wave as it came through the atmosphere (e.g. Tunguska and Chelyabinsk) is more harmful than an iron of comparable size that makes a crater.

In summary, meteorites and meteorite falls provide direct observational evidence for the physics of an asteroid impacting the atmosphere and they provide input data and experimental tests for numerical and theoretical modeling for asteroid deflection and impact should deflection be impossible. Plans for our studies include characterization of the same meteorite samples at both Ames Research Center and Lawrence Livermore National Laboratory.

Introduction

The objects falling to Earth cover a wide range of masses and compositions, and this determines the behavior of the object in the atmosphere and the impact threat [1-4]. At the small end of the mass range we have objects so small that they suffer little or no alteration in the atmosphere and they can be collected by high-flying aircraft for scientific purposes. At the other extreme are massive events that can destroy life on Earth and even produced the Moon from the ejecta. Between these extremes are the events leading to the recovery of meteorites, the production of meteorite craters, and impacts large enough to destroy vulnerable species. Of particular interest here are events larger than those that deposit meteorites and smaller than those that produce major extinctions. Smaller events are harmless, bigger events are best averted by deflection of the incoming asteroid. In other words, we are concerned with the 100-150 m objects, such as that responsible for the Tunguska event, whose approach may be unseen and whose impact may be manageable with sufficient understanding of the process. This paper points out that since such objects are not much larger than the larger of the meteorite-producing events, like Chelyabinsk [5,6, see also 7-10], much can be learned from the study of the meteorites and their fall history. In discussing the relevance of meteorites to planetary defense, we essentially follow a meteorite through its history of atmospheric passage as seen by eye-witnesses and recorded on film and video, especially the light curves, as recovered from impact craters, and as studied in the laboratory. The laboratory studies mentioned are estimates of mass lost in the atmosphere, the measurement of physical parameters relevant planetary defense, the internal structure, composition, meteorite shape and fusion crust, and finally rare meteorites from the surface of the asteroid's regolith.

Observed meteorite falls

As of writing, there are 1723 meteorites in the world's public and private collections that were observed to fall. The fall descriptions range from a few sentences in a newspaper to major technical articles that record hundreds of eyewitness accounts. They are summarized or referenced in the Meteoritical Society's on-line database [11], the product of many long-standing meteorite catalogs. These eyewitness observations are subject to all the well-recognized problems of subjectivity, inexperience, and over-stimulated senses; meteorite fall events are always much bigger events than casual observers realize. Nevertheless, a literature exists for handling subjective eyewitness data in social science and criminal science applications, and it should be possible to derived reliable conclusions about the breadth and detail of fall phenomena by systematically collecting and assimilating eyewitness accounts of observed meteorite falls. A small study along these lines appears in a thesis [12] and a more comprehensive study might prove worthwhile.

Light curves

About 20 observed meteorite falls were recorded by film and video means and quantitative data extracted in the form of light curves, the magnitude of the fireball as a function of time during flight [2, 5-8]. Light curves provide information on the time of onset and extinction of the luminous phase of flight, fragmentation events that appear as flares in the light curve, and the mass of the object can be deduced by model-dependent interpretation of the magnitude of the fireball. At the same time, triangulation of the moving fireball enables its trajectory and velocity to be determined and the mass of the object to be estimated from its dynamics. Most of the existing light curves have been the subject of analysis using simplified models of atmospheric entry (see the references in [2]). However, the interpretation of light curves is hampered by an incomplete understanding of the physics of meteoroid entry into the atmosphere, and fitting numerical models that try to account for the known physics accompanying atmospheric entry are best tested by their ability to reproduce the light curve. Such an attempt is currently being made at Ames Research Center.

<u>Meteorites recovered from craters</u>

In terms of modelling the behavior of objects entering the atmosphere, meteorites recovered from known impact craters offer two important kinds of input data, the final result of the entry process and certainty about the composition and structure of the object that made the crater. The mechanics of crater formation is well understood in a qualitative sense and many numerical simulations exist that describe the process. Thus we know the energy that was deposited into the ground and models of entry and atmospheric passage can be developed. Since we have the meteorites, all the required properties of the projectile that are required by the calculations – density, porosity, composition, tensile and compressive strength, and internal structure, for instance – are known. In fact, in all but one of the 10 instances known [13], the crater forming meteorite concerned was an iron meteorite, whose superior strength and lack of fractures favor survival of atmospheric passage. The largest of the craters with meteorites was produced by a stony meteorite, with properties not unlike the rest of its class. This is not to say that iron meteorites are incapable of fragmenting in the atmosphere. The Sikhote Alin meteorite is an iron meteorite that produced 2500 fragments, many meter-sized boulders and thousands of hand-sized pieces of “shrapnel” [14]. It is not currently clear why this iron fragmented in the way it did or what would have been the outcome if there had been no fragmentation. Modeling the atmospheric passage of crater-forming meteorites is also part of the current planetary defense initiative at Ames Research Center.

Laboratory studies of meteorites

Mass loss. There are many isotopes present in meteorites that were produced by the interaction of high energy cosmic rays with the nuclei of atoms in the meteorite. The nuclear chemistry of the process is well-known through both theoretical and laboratory studies. These “cosmogenic” isotopes build-up in concentration with depth due to a cascade of secondary reactions, and then decrease with depth as energy from the incoming radiation is dissipated through the meteorite. However, the depth profile for each is unique, and by comparing the relative abundance of two isotopes an estimate of the burial depth for a sample can be determined. From this, an estimate of the mass of the object that entered the atmosphere can be calculated. By comparing the estimated mass with recovered mass, an estimate of the mass loss in the atmosphere can be determined. In one study [12], it was found that 23 out of 28 stony meteorites experienced greater than 80% mass loss while four experienced less than 50% mass loss. Only one of the 28 meteorites experienced little or no mass loss in coming through the atmosphere. Such data help place constraints on our theoretical models. There are no plans we know of for the systematic collection of such data, although the required data are usually made available in the regular science literarure for most observed meteorite falls.

Physical parameters. Of course, samples in the laboratory can be subject to an almost infinite array of measurements including those of critical interest to those modeling atmospheric passage [15-17]. At the present time, the critical parameters are thought to be:

- Bulk density
- Porosity
- Compressive strength
- Tensile strength
- Acoustic velocity (longitudinal and shear). From this elastic moduli (Young's modulus and Poisson's ratio) can be calculated.
- Specific heat

Coefficient of thermal conductivity

Thermal emissivity

Laser-driven flow stress

Phase transition pressure

For all of these, recommended procedures are available, either from the appropriate standards institutes or from the literature. These will be measured at Ames Research Center and Lawrence Livermore National Laboratory in a cooperative program of NEO/meteorite characterization.

Internal structure. Meteorites of identical composition but very different internal structure can behave very differently in the atmosphere. Take for example, the ordinary chondrites, the largest class of meteorites in terms of observed falls. A "normal" ordinary chondrite can have physical properties not unlike terrestrial granite, but these rocks are actually from the surface of an asteroid peppered by impact craters of a variety of sizes, covered with a "regolith" (unconsolidated surface layer). Impact craters on Earth and on the Moon have been well studied by geophysical and petrographic techniques and the sequence of rocks associated with them fairly well-know. At the bottom of the crater, and perhaps on the rim, are impact melts, and sometimes these are mixed with target rocks to form impact melt breccias. Some ordinary chondrites have impact melt and impact melt breccia textures, and they are extremely tough. The Novato meteorite is an example [8]. Further from the crater target rocks have been cracked and sometimes the cracks are filled with a black glass. Such meteorites, like Chelyabinsk, are extremely weak [6]. Further out still, are the target rocks unaffected much by the cratering history and they are the unshocked meteorites like Barwell [18] or Peekskill [19]. There are many papers in the literature describing the petrographic symptoms of shock [20], and the fracturing history of meteorites will be documented by a systematic study of cut faces in museums currently being undertaken at Ames Research Center. Fracturing, of course, is arguably the most important property of ordinary chondrites in determining their behavior in the atmosphere.

Bulk composition. The bulk compositions of meteorites are extremely well known, and vary considerably [21-24]. In fact, the 20-30 meteorite classes largely reflect this compositional diversity [25]. This is also true of isotopic composition. For the ordinary chondrites, which might be considered solar condensates, the elements and most isotopes are present in roughly the same proportion as they are in the solar photosphere, gases excepted [e.g. 26]. A fraction of the chondrites, the carbonaceous chondrites, contain large amounts of water, mostly as very fine grained hydrated silicates. These meteorites completely disintegrate in the atmosphere to produce enormous dust trails [27]. Then there are the basaltic meteorites, such as the lunar meteorites, martian meteorites, and Vesta meteorites, as well as the irons, alloys of iron and nickel. Such compositional variation will also produce a range of behavior as these different meteorites pass through the atmosphere.

<u>The shape and fusion crust</u>

The shape of a meteorite can indicate whether the object came through the atmosphere in an oriented fashion – placing it in a maximum drag state – or whether it was tumbling. Orientation usually indicates little or no fragmentation and minimal mass loss. Many large museum display meteorites are oriented, such as the famous Willamette meteorite in the American Museum of Natural History [28].

The heat of atmospheric passage melts the surface of the meteorite and produces a glassy layer (usually black, in stark contrast to the light grey interior) that flows around the sample and produces a trail of small droplets behind the meteorite. This is a very effective way of preventing heat from penetrating far into the meteorite. Under the microscope the fusion crust and the meteorite immediately under the crust show several layers reflecting this process [29]. The top glassy layer usually contains relic grains that did not completely melt and in this glass are very fine grains of magnetite that formed when the glass cooled. Under the melt zone is a layer of partial melting, the lower melting point minerals forming a glass that envelopes the other grains. Below this is a zone in which the lowest melting point phases, eutectics or metal and sulfide, have seeped into the meteorite, filling voids between the unmelted interior grains. Between the first and second zones are relatively large vesicles indicating that gases were formed in this process, presumable oxides of sulfur from the oxidation of troilite (iron sulfide) [30]. It is possible to attach temperatures to the boundaries between each zone and thereby determine temperature gradients and ablation rates [31].

The external texture of the fusion crust depends on orientation during flight, smooth at the front, striated at the sides, and scoriaceous at the rear, and temperature gradients and ablation rates become less from front to sides to rear [32].

The fact that the meteorite is evolving gases during this process, and that quantitative estimates are available for temperature gradients and ablation rates, are useful observational data for entry modelling.

Regolith meteorites

Researchers interested in the deflection of incoming asteroids using stand-off nuclear explosions or laser-based methods, rely on knowledge of the composition and texture of the very surface layer. Unfortunately, asteroids are covered with a reasonably thick layer of regolith (unconsolidated fine material) that is immediately lost during atmospheric entry and will not survive atmospheric passage. However, there are a group of meteorites, probably numbering around 50 at the present time, which are lithified regolith samples. These are the "gas-rich regolith breccias" and they are noted for their unusual brecciated texture of "light clasts" embedded in "dark matrix" [33]. The clasts are perfectly normal samples of meteorite with all the properties typical of their class. The dark matrix is material made by the comminution of these clasts and its exposure to the space environment, most particularly exposure to the Sun. Thus in the dark matrix there are trapped solar wind atoms and charged-particle tracks. These solar particles have very limited penetrability, a few tens of micrometers, their presence indicates that at one time there was literally nothing between the matrix grains and the Sun. The reason these matrix samples survived passage to Earth is that some event, probably micrometeorite impacts over millions of years, lithified the dust, making it a coherent rock [34]. The lithification process altered the physical properties of the regolith sample, but never-the-less these are minimally altered samples of asteroid regolith.

Conclusions

Meteorites can inform us about the entry of small asteroids into the atmosphere in many ways; eye-witness observations of meteorite falls, quantitative information from camera and video recorders, impact craters and the rocks that caused them, laboratory studies like mass loss determination, studies of the fracturing of meteorites, determination of a broad range of their physical properties, detailed studies of the way in which the meteorite surfaces react during atmospheric passage. Finally, there are the rare meteorites that were once part of the asteroid regolith that carry information about the very surface of asteroids. No doubt, we can expect surprises as we progress with the challenge of developing planetary defense strategies, but studies of the type detailed and proposed here will likely be of considerable value in our efforts to develop deflection techniques and impact assessment methods.

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