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Review Article

A meteorite perspective on asteroid hazard mitigation

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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. We describe six ways in which they have relevance to understanding the behavior of meteoroids in the atmosphere and thus impact mitigation. (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 19 recovered meteorites, film or video recordings have been obtained and for most of these light curves have been derived which provide quantitative information on meteorite fall and fragmentation. (3) There are 188 known meteorite craters on Earth and in 10 cases fragments of the meteorite responsible have been recovered. In these cases numerical impact models can utilize the known properties of the projectile and the dimensions of the crater. (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 understanding the 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" provide information on the outermost layer of the parent asteroid from which the meteorites came. This information is critical to certain mitigation strategies. We conclude by describing initiatives for hazardous asteroid impact mitigation at Ames Research Center and Lawrence Livermore National Laboratory that will exploit and disseminate the information available from meteorites. This includes characterization of the meteorites likely to be analogous of incoming asteroids and the development of a website to advise the world-wide community of information available.

Contents

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1. Introduction

With the realization that asteroid impact can cause major biological extinctions (Alvarez et al., 1980; Schulte et al., 2010), the discovery of large numbers of asteroids in the vicinity of the Earth (Stuart and Binzel, 2004), and the recent major meteorite fall in Chelyabinsk, Russia (Popova et al., 2013), there is considerable interest in developing means to protect the Earth from asteroid impact or predicting the result if deflection fails (Gehrels, 1993; Belton et al., 2004). Various space agencies are making asteroid missions a high priority (Russell et al., 2007; Sierks et al., 2011; Fujiwara et al., 2006; Lauretta, et al., 2012). In this paper, we consider the types of information that may be helpful to the asteroid impact hazard mitigation effort that are available from meteorites, the rocks that survive the passage of an asteroid, or asteroid fragment, through the atmosphere. There are, of course, major volumes and even textbooks that describe meteorites (Kerridge and Matthews, 1988; Lauretta and McSween, 2006) but the relevance of meteorites to asteroid impact hazard mitigation has never been appropriately summarized. Furthermore, the current information is by no means comprehensive when we think in terms of the asteroid impact hazard. This paper is a survey of current information on meteorites and indicates what further studies should be undertaken in order to best contribute to the international asteroid impact hazard effort.

First, by way of background, we mention the wide variety of behavior that is to be expected by the wide variety of sizes of objects entering the atmosphere (Fig. 1). The smallest objects entering the atmosphere are decelerated without significant heating (Öpik, 1958). These dust particles are routinely collected by stratospheric aircraft flights (Brownlee, 1985; Brownlee et al., 1997). Larger particles are responsible for meteor showers and deposit most of their energy in the form of an ionization trail and associated visible radiation with a small amount consumed during fragmentation and ablation (Öpik, 1958). For objects reaching the meter scale, there are also significant sound effects and a blast wave. Most meteorites are in this size range. Meteors and meteorites deposit ablation spherules in the atmosphere which are also collected by the stratospheric flights (Brownlee et al., 1975). Larger meteorite falls (~20 m), like Chelyabinsk, dissipate more of their energy as sound and blast waves and less as ionization and radiation (Popova et al., 2011). Larger still (~50 m), and Tunguska-like events result (Chyba et al., 1993), or small impact craters like Meteor Crater are produced (Artemieva and Pierazzo , 2009), depending on the properties of the object and its trajectory. Larger still, in the 100–500 m size range, major craters are produced and considerable energy goes into producing the crater and small amounts of ejecta. Finally, in the 10 km range, considerable energy goes into the ejecta, which encircles the Earth and causes climate change. The K–T (now K-Pg) event is an example of such an impact (Schulte et al., 2010).

In the context of asteroids being hazardous to Earth, objects smaller than a few 10s of meters will produce little damage and the main interest lies in collecting whatever samples are available to enhance our museum collections. Objects in the 10 km range, and perhaps as small as the 500 m, will wreak havoc and there is probably little that can be done to handle the effects of an Earth impact. The main hope lies in deflection, and objects these sizes are relatively easy to detect (Gritzenr and Kahle, 2004). Thus it is the 50–150 m objects that are difficult to detect but could produce major regional damage on impact. Thus it is the 50–150 m objects that we need to understand, in particular their behavior in the atmosphere (Johnson, 2015). This way we can determine the best means of handling such an impact. It has often been remarked that an 50 m iron meteorite could destroy a major city like Chelyabinsk or New York (e.g. Artemieva and Pierazzo, 2009).

The present paper will review the diverse range of information that can be derived from meteorites. Such information clearly has the potential to inform our efforts relating to hazardous asteroid impact. We begin by reviewing fall phenomena. Eyewitness fall descriptions provide qualitative observations of fall phenomena that might include details not yet recognized. The value of the light curves for meteorite falls is well recognized and there are many literature studies based on this. Studies of the shape and fusion crust are few, but they provide quantitative information on orientation, thermal gradients, and ablation rates. Furthermore, a wealth of data exists on the compositional and petrographic studies that point to the wide range of material entering the atmosphere. The 10 impact craters with associated meteorite fragments provide a test for models for quantitative models of the larger objects. Finally, laboratory studies provide detailed information on a wide variety of properties relevant to the asteroid impact hazard effort, ranging from mass loss in the atmosphere, to the internal structure of objects entering the atmosphere, to information on asteroid surface rocks (i.e. the gas-rich regolith breccias) and measurements of their physical properties. They also provide information on the way meteorites fracture and this may serve as a guide to the possible fracture behavior of incoming objects.

2. Fall phenomena

2.1. Observed meteorite falls provide observational information on the behavior of objects passing through the atmosphere

According to the Meteoritical Society database (accessed June 24, 2015), there are 1274 meteorites in the world's collections,

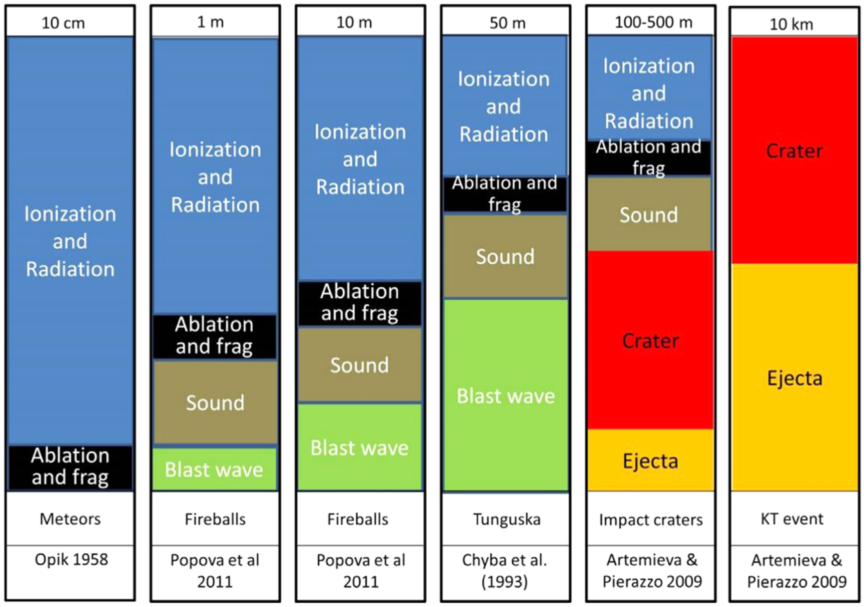

Fig. 1. Schematic diagram suggesting the various means of energy deposition for objects of a wide range of mass entering the atmosphere. (reader beware: this is a notional plot based on a qualitative reading of the literature and is not based on calculations. Details for a particular fall will depend on many factors, like trajectory, meteoroid composition, and internal fracturing.).

Table 1
Summary of the fall descriptions of 20 meteorites in the Meteoritical Bulletin, April 1960–November 1970, (Sears, 1974).

Feature	No of descriptions mentioning feature No.	%
Explosion	17	85
Rumbling	7	35
Whistling	9	45
Impact sounds	4	20
Light	11	55
Flares	2	10
Dust trail	6	30

public and private, that were observed to fall. For the majority of these, the database records date, time of day and location and a brief description of their fall. Some authors have tried to derive information concerning meteorite sources from time of fall (Wetherill, 1968; but see Morbidelli and Gladman, 1998). For a few of them, the literature contains detailed descriptions of their falls. By way of example, Sears (1988) summarized the fall descriptions of six Arkansas meteorites. Similary, Sears (1974) summarized the fall descriptions of 20 meteorites that fell between April 1960 and November 1970 in table form (see Table 1) using data from the Meteoritical Bulletin (the predecessor of the Meteoritical Society database). Eyewitness descriptions of meteorite falls are notoriously subjective, especially since the event is so unusual. It has often been noted that observers invariably think the fireball, so much brighter than anything commonly experienced, is closer than it really is (Nininger, 1952).

Some of the subjectivity of eyewitness observations of fireballs has been removed by the availability of photographic networks (McCrosky and Ceplecha, 1969; McCrosky et al., 1971; Halliday et al., 1978; 1981) and, more recently, the advent of personal video equipment (Brown et al., 1994; Popova et al., 2011). Nineteen fireballs have been recorded this way and for most of them detailed information on the trajectory and behavior in the atmosphere have been documented (Table 2).

In addition to flight behavior, information about objects entering the atmosphere can be gleamed from the distribution of the fragments of a meteorite fall on the ground, the so-called "scatter ellipse" (Krinov, 1974; Passey and Melosh, 1980). In the case of the Sikhote Alin fall in eastern Siberia in 1947, not only were there three overlapping scatter ellipses, there were numerous impact pits (Krinov, 1966). There were many larger (~50 cm) fragments, which tended to land further along the line of flight since their momentum was greater, but also produced a considerable number of smaller (~5 cm) fragments that formed highly angular pieces with sharp edges commonly referred to as "shrapnel". Krinov produced a diagram describing how he could reconstruct the parent object from the distribution of fragments and impact pits (Fig. 2).

The U.S. government has detected large meteoroids in the atmosphere using its nuclear monitoring satellites (Tagliaferri et al., 1994). Data are slowly being placed on public database (http://neo.jpl.nasa.gov/fireballs/). A few meteorites have been recovered after detection in space (e.g. Jenniskens et al., 2009), but most of the government observations to date are just airblasts. These observations do afford an additional source of information on the nature of the asteroid hazard to Earth.

2.1.1. The value of fireball and scatter ellipse observations to the asteroid hazard

While highly subjective, meteorite fall observations provide direct observational data from which to derive an understanding of the behavior of objects flying through the atmosphere at interplanetary velocities. To combat the subjectivity of these observations, we have a large number of observations and there are commonality and trends that suggest a core of accuracy and reliability in these accounts. The data in Table 1 are meager and merely hint at what a careful and systematic combing through the fall descriptions might yield in the way of detailed information on fall mechanics. It is a resource currently untapped, except for the spectacular and recent Chelyabinsk fall. In fact, there is a danger that excessive focus on this one fall will miss information available when a range of sizes, shapes, compositions, physical properties, and trajectories are systematically examined. Observations of the scatter ellipse provide information on flight details and fragmentation history.

Table 2
Meteorite falls for which video recordings are available.

Meteorite	Date	Reference
Pribram	1959-4-7	Ceplecha (1961), Spurny et al. (2002, 2003)
Lost City	1970-1-4	McCrosky et al. (1971), Ceplech (1996), Borovička and Kalenda (2003)
Innisfree	1977-2-6	Halliday et al. (1978, 1981)
Peekskill	1992-10-9	Brown et al. (1994), Ceplecha (1996)
Tagish Lake	2000-1-18	Brown et al. (2000), (2002a, b)
Moravka	2000-2-6	Borovička et al. (2003a, b)
Neuschwanstein	2002-5-6	Spurny et al. (2002, 2003)
Park Forest	2003-3-27	Brown et al. (2004)
Villalbeto de la Pena	2004-1-4	Trigo-Rodríguez et al. (2006)
Bunburra Rockhole	2007-7-20	Spurny et al. (2009), Bland et al. (2009)
Almahata Sitta	2008-10-7	Jenniskens et al. (2009), Borovička and Charvat (2009)
Jesenice	2009-4-9	Spurný et al. (2010)
Grimsby	2009-9-26	Brown et al. (2011)
Košice	2010-2-28	Tóth et al. (2015)
Sutter's Mill	2012-4-22	Jenniskens et al. (2012)
Novato	2012-10-17	Jenniskens et al. (2014)
Chelyabinsk	2013-2-15	Popova et al. (2013)
Jinju	2014-3-9	Meteoritical Society Database, accessed 2015-9-18 says several dashboard video records were obtained.
Žďár nad Sázavou	2014-12-9	Meteoritical Society Database, accessed 2015-9-18 says 10 fireball network video records were obtained.

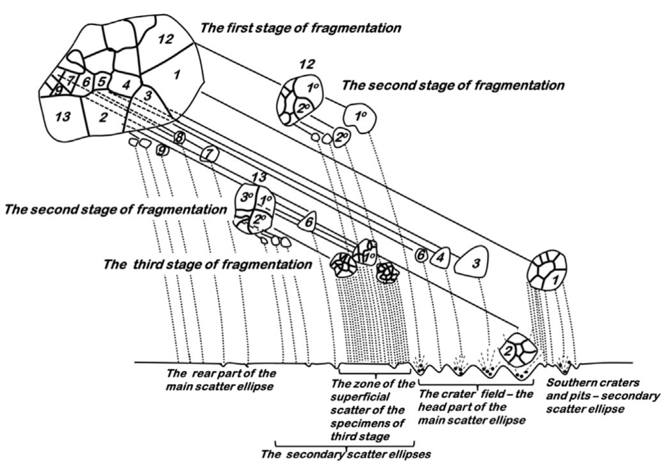

Fig. 2. Diagram by Krinov describing the manner in which he reassembled the incoming Sikhote Alin meteorite from the distribution of fragments and impact pits on the surface of the Earth (Krinov, 1974, 1981).

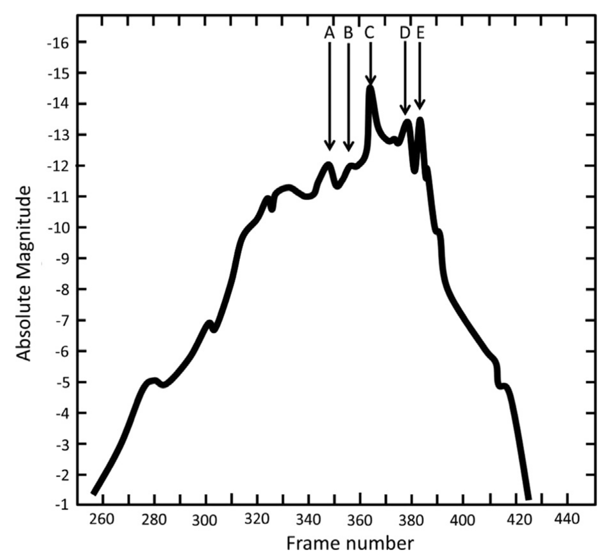

Fig. 3. Light curve for the Grimsby meteorite with the five flares indicated A–E indicated, the main flare being C (Simplified after Brown et al., 2011, where details can be found).

2.2. Light curves provide the only quantitative observational data with which to build and test numerical models of the behavior of meteoroids passing through the atmosphere

Light curves have been important sources of quantitative information on the fall of a meteorite since the first curves were obtained by the camera networks in the 1960s (McCrosky and Ceplecha, 1969). Light curves enable the time of onset of visible radiation and its extinguishing, the maximum magnitude reached and when, and the identification of flares which most probably represent major disruption events (Fig. 3). Most importantly, they provide two independent measures of the mass of the object, one based on the movement (the “dynamic mass”) and one based on magnitude (the “photometric mass”). Reconciling these values has long been a concern in understanding light curves (Ceplecha, 1966). With the advent of modern computing technologies, hydrodynamic codes of increasing sophistication are available to help understand and predict this process (e.g. Svetsov et al., 1995).

2.2.1. The value of light curves to the the asteroid impact hazard effort

Light curves are the ultimate observational test of the validity of entry calculations because they are one of the few pieces of direct, quantitative data we have on the atmospheric passage of natural objects passing through our atmosphere. Models can be created using the laws of physics, observations from meteorites and meteorite falls, and input data from sources described elsewhere in this article, and synthesized in the form of numerical calculations using a variety of models that can be tested against the available light curves.

2.3. Shape and fusion crust studies provide information on fragmentation and ablation

In the 1977 Harvey Nininger wrote two books on meteorite shapes and orientation which essentially went unnoticed (Nininger, 1977a, b). In fact, the shapes of meteorites, as well as the texture of the fusion crust and the petrography of the meteorite through and immediately under the fusion crust, can provide an additional kind of information on atmospheric passage.

First, the shapes of meteorites vary widely, as might be expected for the products of a fragmentation process (Nininger, 1977a). However, a noteworthy number of them, perhaps 25%, have conical shapes which have been ascribed to orientation in the atmosphere, i.e. turning the maximum drag cross-section to the line of flight, followed by sculpturing in the air stream which produces a cone with the apex in front (Farrington, 1915). One of the best examples of this is the Willamette iron meteorite (Fig. 4) which was discovered in a forest in Oregon in 1902. The meteorite was half buried in the soil for ~13,000 years and this resulted in huge holes produced by weathering (Ward, 1904; Mason, 1964). Orientation increases the chances of a meteorite surviving atmospheric passage.

Fig. 4. The Willamette iron meteorite on the cart used by Ellis Hughes and his companion to move the meteorite from the find site to their farm. The conical shape is typical of meteorites that assumed an oriented position in the atmosphere. The holes along the base of the meteorite are the effects of weathering. (From Ward, 1904).

The fusion crust is the dark surface material on meteorites that is produced during atmospheric flight (Ramdohr, 1963). It is very thin, usually less than a millimeter, and thinner at the front of the meteorite (i.e. leading face during atmospheric passage) and thickest at the rear, with lateral faces being intermediate, although it may sometimes pool in depressions on the surface to be as much as two millimeters thick Sears and Mills (1973). The black layer consists of glasses in which are embedded mineral grains that have resisted melting and tiny skeletal grains of magnetite that crystallized when the crust cooled (Sears, 1974; Fig. 5). Under the glassy zone is a partial melt zone characterized by a layer of vesicles (gas bubbles) and under that is a zone of unmelted crystals that are surrounded by metal and sulfide eutectics (low melting point mixtures), sometimes referred to as the penetration zone. Sears and Mills (1973) assigned temperatures to the interfaces of these zones and thereby determined the thermal gradients in the meteorite produced by the heat of atmospheric passage. From these temperature gradients, ablation rates can be determined. These were found to be 0.35 cm/s at the smooth front surface, 0.27 cm/s at a smooth lateral face, 0.22 cm/s at a lateral, striated face, and 0.18 cm/s at a warty (scoriaceous) rear face. These values are similar to those for iron meteorites, apparently a lower heat capacity is offset by a lower melting temperature (Lovering et al., 1960).

2.3.1. The value of shape and fusion crust studies to the asteroid impact hazard effort

The shapes of the meteorites and the fusion crust textures provide information in the orientation of the surface or the whole object during flight. Fusion crust studies show that, at least during the final stages of flight, fusion crust development is a very effective way of protecting the meteorite during flight and very little heat actually penetrates into the meteorite, the heat of entry being carried away as melt droplets that stream behind the

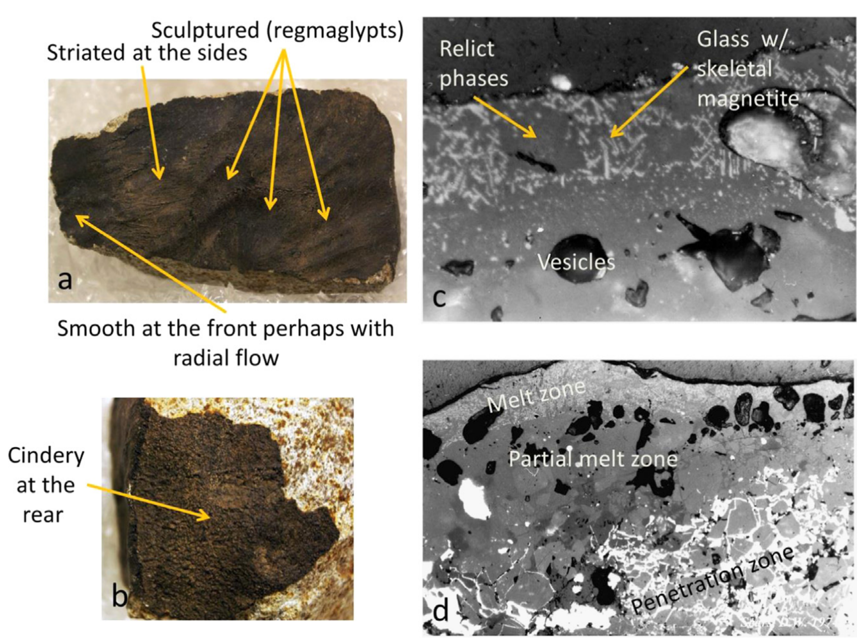

Fig. 5. The textures on the fusion crust of meteorites and the detailed petrography under the fusion crust enable information to be determined on the orientation of the face, thermal gradients, and ablation rates (Sears, 1974a; Sears and Mills, 1973). (a) Lateral face of one piece of the Barwell meteorite, about 15 cm long, with a slight curvature showing some frontal face. Stria of once-melted crust flow back from the smooth front and over the sides and regmaglypts ("thumb-prints") have been excavated on the sides by turbulent air flow. (b) The rear facing end of the fragment of the Barwell meteorite, about 12 cm across. Protected from airflow, the fusion crust is thick and cindery. (c) Reflected light microscopic image of the outer section through the fusion crust. The outer zone, the "melt zone", consists of glass with exclusion submicron crystals of magnetite and relic grains of refractory minerals. Below this is a "partially melted zone" which includes vesicles (gas bubbles) presumably made by the release of SO_2 and SO_3 as the mineral troilite (FeS) is oxidized by reaction with the atmosphere. Vertical field of view about 100 μm. (d) A section through the fusion crust, and immediately underneath, about 400 μm deep, showing the melt zone, the partial melt zone, and the "penetration zone", where Fe and FeS eutectics have melted and flowed into cracks between the underlying mineral grains. (images from Sears, 1974a; Sears and Mills, 1973).

meteorite. In fact, most of the interior the meteorite suffers little or no heating during atmospheric passage (Sears, 1975). These are quantitative, observational data that can be used to test numerical models of ablation and fragmentation during atmospheric passage. In addition, detailed petrographic observations provide information on the melting and ablation process, for example the presence of vesicles indicates considerable degassing. Vapors surrounding the meteoroid will strongly influence the process of atmospheric passage.

3. Meteorite diversity suggests that many kinds of behavior will be observed during atmospheric passage, consistent with fireball observations

Meteorite classification, like so many classification schemes for natural objects, has undergone a long and complex history resulting in a hierarchal scheme of classes, clans, and groups in which there are nearly 50 discrete entities (Fig. 6). Mostly, meteorite classification is based on bulk elemental composition (Jarosewich 1990; Wiik, 1969; Wasson and Kallemeyn, 1988), which is reflected in the mineralogy of the meteorites, but sometimes isotopic measurements and petrography are also invoked (Clayton, 2010). However, it is possible to recognize much coarser divisions and these are indicated by the ellipses superimposed on the classes in Fig. 6.

Some meteorites have compositions very similar to the Sun's photosphere, setting aside the elements that would be gaseous at room temperature. These are the chondrites, and they have a characteristic internal structure that has been described as "sedimentary". Some of the chondrites are water-rich, being 10–20 volume percent water. The minerals in these meteorites are hydrated, so the meteorites might be best regarded as "mud balls". Then there are a relatively small number of meteorites that have solar compositions but appear to have been melted. They are referred to as "solar but igneous" in Fig. 6 and more generally as the "primitive achondrites". Then there are the meteorites that differ from solar in major ways and in many respects resemble the igneous rocks found on planetary bodies like the Earth, Mars and the Moon. These are the basaltic meteorites. Finally, there are the iron meteorites, and the stony-iron meteorites, which contain

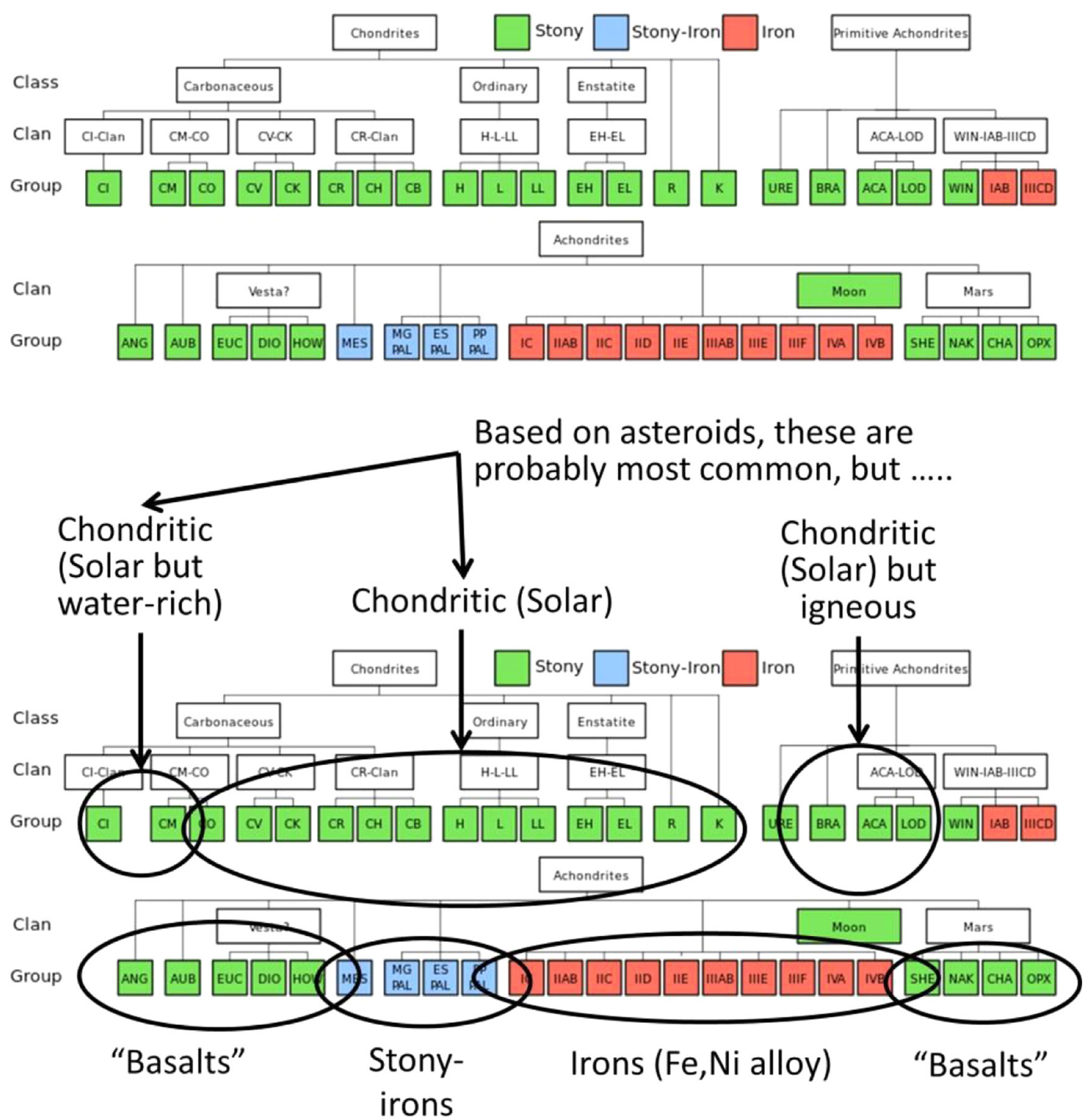

Fig. 6. There are now almost fifty discrete classes of meteorites, based on their elemental and isotopic composition and their petrology. They range from water-rich "dust balls', to rocks resembling condensed solar materials, to basalt-like rocks, to metallic objects. (Modified after Weisberg et al., 2006).

large amounts of metal and also appear to have had an igneous history of some kind.

This brief and simplified summary does not do justice the enormous amount of work that has been invested in each and every type of meteorite represented in Fig. 6. Based on the distribution of asteroid classes, and their likely meteorite associations, it is probable that the asteroids or asteroid fragments entering the atmosphere might be the water-rich and water-poor chondrites in almost equal numbers with the others being less than ~10%.

Meteorites are not only diverse in their chemical classes, but they have a variety of physical histories. Probably most widespread process they have experienced is parent body metamorphism, which is heating while in the solid state (Huss et al., 2006). Such a heating process is well-known on Earth and is normally produced by deep burial so that the heat generated by radioactive elements in the planet cannot escape. The process is much more intense on Earth, where wholescale changes to the rock can occur; mineral make-up as well as texture is affected and an entirely new type of rock results (Bucher and Frey, 1998). For meteorites the process seems relatively mild and results in the homogenization of minerals, blurring of textures, crystallization of amorphous material (including glass) and a coarsening of small mineral grains. "Petrographic types" are assigned to the meteorites which describe the level of alteration by this process; type 3 to type 6 for ordinary chondrites (Van Schmus and Wood., 1967). There is some further subdivision within the type 3s because the metamorphic range within them is so large, and this can be measured by sensitive instrumental methods (e.g. thermoluminescence, Sears et al., 1980a). Thus we have types 3.0 to 3.9. It seems likely that metamorphism would change the physical properties of meteorites by increasing their strength, although this has yet to be shown.

The types 1 and 2 were once thought to be the least metamorphosed meteorites, but they are now thought to be altered by a different process, namely the introduction of large amounts of water, so that the anhydrous mineral characteristic of ordinary chondrites are essentially absent to be replaced with water-rich phyllosilicate minerals (Brearley, 2006). These are the CI and CM meteorites referred to above.

A long-term mystery in meteorite studies was the source of the heat that caused the metamorphism. The initial assumption was that it was long-lived isotopes of Pb, U, and Th, the source of the terrestrial heat flux, but this required 800 kilometer sized bodies which were essentially absent in the solar system, only the dwarf planets Ceres and Pallas are this large, the thousands of asteroids thought to be the parents of meteorites a few hundred kilometers in size. Then in 1976 evidence for ^{26}Al being present when the meteorites formed (Lee et al., 1976) was discovered and the problem became one of why are so few asteroids melted, since aluminum is abundant ^{26}Al is highly radioactive? Small changes in time and place can be invoked to explain both why ordinary chondrites are metamorphosed in the way they are and why some asteroids and their resulting meteorites are igneous rocks.

Differentiated bodies are those that have been fully melted and have segregated into cire, mantle and crust, and the Earth is typical of such a body (McCoy et al., 2006). The crustal rocks produced by such a process are familiar, and are basalts or related rocks, these are high in the elements present in low density minerals that float to the surface and depleted in elements that tend to alloy with metallic iron and go down to the core. A small but significant number of meteorites are basalts or otherwise the result of these wholescale melting events and an even smaller fraction of the observed falls are iron meteorites or their relatives (Goldstein et al., 2009). Missing from the meteorite population are the mantle-type (olivine-rich) rocks, although olivine-rich asteroids are known. Because of their igneous history, such rocks are expected to be strong, dense, and have low porosities.

Shock is also a common cause of alteration among meteorites and probably plays a major role in determining atmospheric behavior. The term "shock" in the meteorite literature refers to changes caused by sudden excursions to elevated pressure and then relatively rapid cool down (Stöffler et al., 1988). As a result of this process, the rock is suddenly heated and then cools relatively slowly. During a shock process, which is normally caused by an impact between two asteroids, or between the meteorite parent body and an incoming asteroid, there is considerable fracturing, melting, and mixing, and the heating causes mineralogical changes and melting or iron and sulfides which flow long distances down the fractures to produce "veins". Chelyabinsk is an excellent example of a heavily shocked meteorite with abundant veins and shock melted fragments ("clasts") and this is why it fragmented so much in the atmosphere and produced a large number of small meteorites.

3.1. The value of meteorite taxonomy, with fall observations described in the previous section, to the asteroid impact hazard effort

For a given trajectory, the great diversity in meteorite compositions and physical histories indicates that we should expect a great diversity of behavior in the atmosphere. Knowledge of this meteorite diversity, and experience with observed meteorite falls, suggests that there are a large number of different types of behavior for objects moving through the atmosphere (Fig. 7). Irons, like Willamette (Ward, 1904), will undergo smoothing (unless they are already fairly rounded in shape) and then orientation so they land as conical shapes (Farrington, 1915). They may spall bits during flight, as protuberances are worn away, and they may shed shards from the rear near the end of their flights, as the Canyon Diablo meteorite did (Artemieva and Pierazzo, 2009), but they essentially reach the ground without significant mass loss. Peekskill and Chelyabinsk are two stony meteorites that behaved very differently, Peekskill producing a few major fragments (Brown et al., 1994) and Chelyabinsk a large number of small

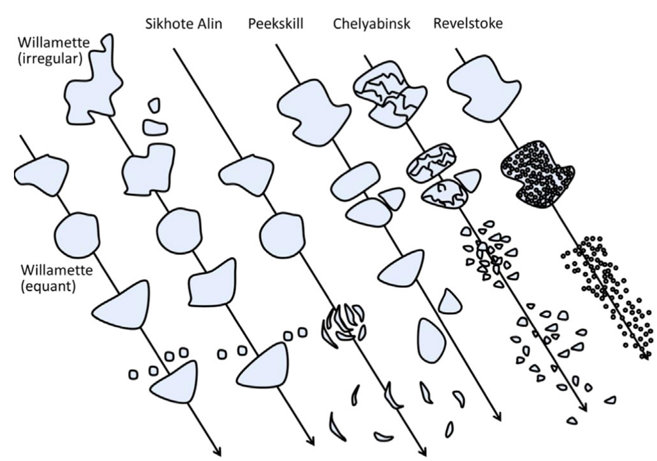

Fig. 7. Based on the variety of meteorite classes and their properties, and fireball observations, it is possible to predict a variety of behavior for objects entering the atmosphere. Metallic objects like Willamette, that have high tensile strengths and become oriented in the atmosphere, probably fragment relatively little, although if highly irregular in shape when they entered the atmosphere they will have become rounded as torque forces removed protuberances. Sikhote Alin is an iron meteorite that did not orient itself and underwent violent disruption producing many large fragments and a considerable amount of "shrapnel" (See Fig. 2). The "dust balls", like Revelstoke, disintegrate and produce mostly clouds of dust. Between these extremes are stony meteorites, like Peekskill and Chelyabinsk, whose behavior is determined by their internal fracture structure before they entered the atmosphere.

(pea-sized) fragments in addition to the very weak 550 kg fragment pulled from a lake (Popova et al., 2013). Chelyabink's behavior was determined by the large number of fractures in the rock that entered the atmosphere. The effects of fracturing are discussed below. Revelstoke, a water-rich chondrite, largely disintegrated in the atmosphere to produce prodigious amounts of dust and only a single tiny fragment that reached the ground (Carr, 1970).

4. Meteorite fragments from craters provide two important parameters for modelers, the meteorite and the crater

Of the 188 known meteorite impact craters on Earth, about 10 have meteorite fragments associated with them (Koeberl, 1998); almost certainly they are pieces of the object that made the crater (Table 3). All are very small and were all by iron meteorites. The best known in the list is the Meteor Crater in Arizona, USA, the first crater to be recognized as being formed by meteorite impact. This was confirmed by the presence of high-pressure mineral phases in the crater rocks (Chao et al., 1962).

5. Laboratory studies of meteorites

Sufficient laboratory studies have been performed on meteorites to fill large multi-authored works (e.g. Kerridge and Matthews, 1988; Lauretta and McSween, 2006). We will draw attention to a few that we consider to have particular significance for the asteroid impact hazard effort. These are studies that relate to preatmospheric size, internal structure, regolith breccias, and the physical properties needed to understand behavior of meteorites in the atmosphere and the surface nature of asteroids.

5.1. Preatmospheric size determinations relate to fragmentation processes and provide another parameter with which to test entry models.

It was in the 1940s and 1950s that unusual isotopic abundances were detected in meteorites that were ultimately ascribed to the production of isotopes by the interaction of high energy cosmic rays with nuclei in the meteorite (e.g. Fireman, 1958). The products of these reactions are referred to as the cosmogenic isotopes. Proof that this mechanism was effective was the existence of profiles that reflected the shape of the meteorite in space (e.g. Fireman, 1958). Thus the level of these isotopes in a particular sample is affected by its burial depth during cosmic ray exposure. This situation also means that it is possible to use the abundance of cosmogenic isotopes in meteorites to determine the preatmospheric mass of a given meteorite and thereby the percent of mass loss during atmospheric passage. A summary of mass loss of 30 stony meteorites is given in Fig. 8. The majority, 22, had experienced greater than 80% mass loss. On the other hand, four suffered mass losses of 50% or less. One seems to have experienced little or no mass loss in coming through the atmosphere.

5.1.1. The value of mass loss determination in the asteroid impact hazard effort

The amount of material lost during atmospheric passage is important information in understanding atmospheric behavior of meteorites. The explanation for this range in mass losses involves many factors, like composition and dynamic considerations, but almost certainly a major factor is the internal structure of the meteorites discussed in the next section.

5.2. Internal structure determines fracture behavior in the atmosphere, arguably the most important single factor in determining the atmospheric behavior of meteoroids

In addition to covering a wide range of compositions, meteorites display an enormous range of internal structures which are often independent of composition (Fig. 9). The mixture of minerals making up most meteorites, let's say the ordinary chondrites, results in a uniform pale gray appearance. This is often observed. However, there are a significant number, ~13.5% (Britt and Pieters, 1991), that have a uniform fine-grained black appearance. These are the famous shock-blackened ordinary chondrites. They have young ages (~500 Ma) and petrographic evidence for considerable shock heating (for example, melted sulfides and deformed mineral grains). Other ordinary chondrites are much tougher and consist of mechanical mixtures of pale gray and shock blackened material bound together by a ubiquitous glass. Such structures are commonly found in rocks around craters on the Earth and Moon and are referred to as impact melt breccias. In between these extremes is probably the most common type of defect structure where prolific cracks throughout the meteorite are filled with a black glass in which there is finely dispersed metal and sulfide grains. These types of shock veins considerably weaken the meteorite. A final type of structure that may facilitate fragmentation in the atmosphere for iron meteorites involves crystal structures. The Widmanstatten structure consists of the two common phases of iron–nickel alloy in crystallographic orientation and iron meteorites could potentially cleave along the interfaces.

Table 3
Terrestrial impact craters with diameters >0.1 km with meteorite fragments (Koeberl 1998)[a].

Crater	Country	Diameter (km)	Location	Meteorite
Wabar	Saudia Arabia	0.10[b]	21°30'N, 50°28'E	Iron (IIIAB)
Kaalijarvi	Estonia	0.11[b]	58°24'N, 133°09'E	Iron (IAB)
Henbury	Australia	0.16[b]	24°35'S, 133°09'E	Iron (IIIAB)
Odessa	USA	0.17[b]	31°45'N, 102°29'W	Iron (IIIAB)
Boxhole	Australia	0.17	22°37'N, 135°12'E	Iron (IIIAB)
Macha	Russia	0.3[b]	59°59'N, 118°00'E	Iron (Iron)
Aouelloul	Mautritania	0.4	20°15'N, 12°41'W	Iron (IIIB, IIID?)
Monturaqui	Chile	0.46	23°56'S, 68°17'W	Iron (IAB)
Wolf Creek	Australia	0.9	19°18'S, 127°46'E	Iron (IIIAB)
Meteor	USA	1.2	35°02'N, 78°29'W	Iron (IAB)

The value of craters with meteorite fragments for asteroid hazard mitigation. The significance of craters and their projectile fragments is that we have two critical pieces of information in modeling the flights of these objects through the atmosphere, the projectile and the final result.

[a] Not included here are craters where the nature of the impactor has been inferred from soil chemistry. The recent Carancas anomalous impact feature in Peru is not included because of its small size, neither are the impact pits at the Sikhote Alin other meteorite fall sites which are not hypervelocity impact craters.

[b] In these instances, the impact resulted in many craters and the diameter cited above refers to that of the largest crater.

5.2.1. The value of meteorite fracture studies in the asteroid impact hazard effort

It is evident from many studies of meteorite passage through the atmosphere (e.g. Baldwin and Sheaffer, 1971) that fragmentation is probably the single most important factor in determining how much material reaches the surface and the damage done. Meteorite studies provide insights into the nature of the fragmentation process for these objects and they provide some quantitative data that may be extrapolated to larger objects using, for instance, the Weibull parameter (Frechet, 1927; Weibull, 1939, 1951). Such studies are especially valuable when it is recalled that shielding by fragments that fly in a group means that weaker material is protected (Dinesh Prabhu, personal communication). Thus the often repeated statement that only the tough material reaches the surface may not be true.

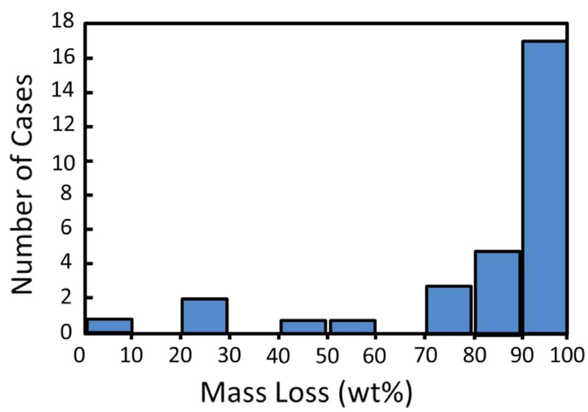

Fig. 8. The mass of a meteorite prior to entering the atmosphere can be determined from the abundance in the meteorite of cosmogenic isotopes, namely isotopes produced by interactions with cosmic rays. Of the 30 stony meteorites shown here, 22 had experienced greater than 80% mass loss and 4 less than 50%. One seems to have experienced little or no mass loss in coming through the atmosphere. (Data from Sears, 1974a).

5.3. Regolith breccias provide insights into the very surface of asteroids, which is especially relevant to the development of deflection techniques.

Another rare group of meteorites (~3%, Britt and Pieters, 1991) that have particular significance for the asteroid impact hazard are the gas-rich regolith breccias (Fig. 10; Goswami et al., 1984). These meteorites were first noted for the very high, but non-reproducible, abundances of trapped gases. The nature of these gases, mostly inert gases with mass numbers a multiple of four (^{4}He, ^{20}Ne, ^{36}Ar as well as ^{12}C), suggested that they were trapped solar wind. It was quickly realized that the poor reproducibility was caused by the gases only being present in the “dark matrix”, the “normal” part of the meteorite being referred to as “light clasts”, so the analyzes were reflecting the proportion of light to dark material being analyzed. New discoveries followed in rapid succession that confirmed this interpretation for these unusual rocks. These were rocks made by a lithification process (Bischoff et al., 1983) from the dust, gravel, and stones lying on the very surface of the asteroid.

5.3.1. Value of gas-rich regolith breccias to the asteroid impact hazard effort

Gas-rich regolith breccias have particular significance as they come from the very surface of their parent object. They have particular relevance to deflection techniques, where a detailed knowledge of the asteroid surface is required.

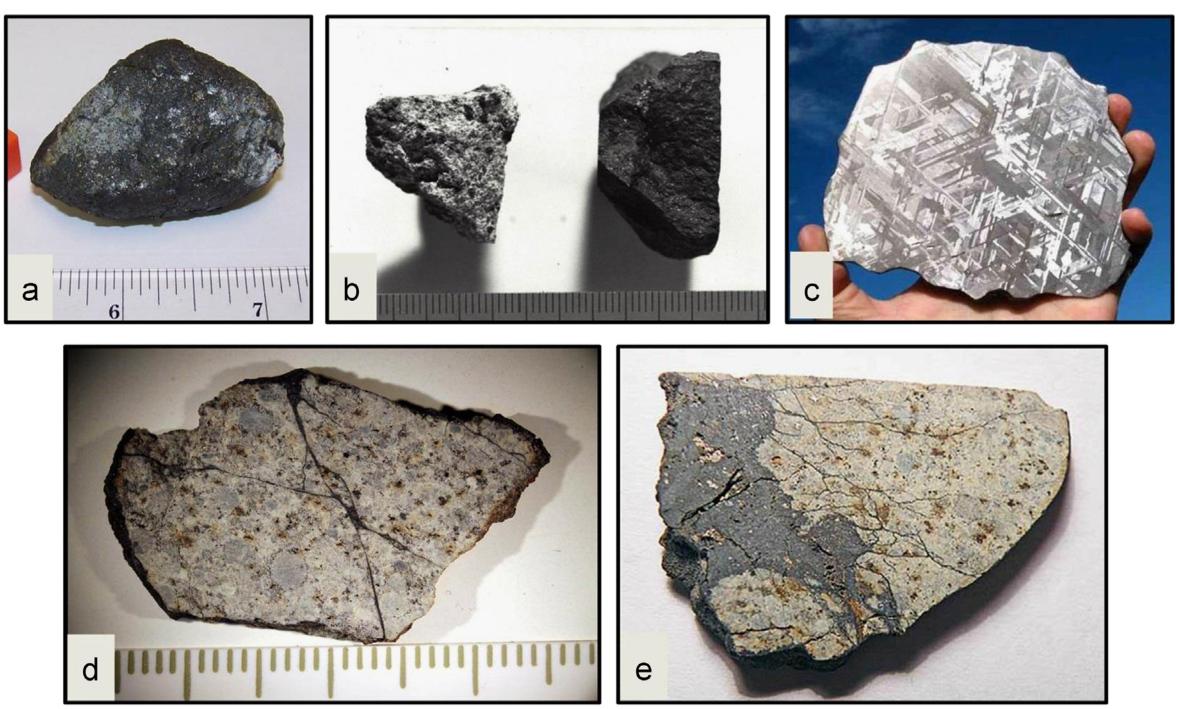

Fig. 9. Internal structure plays a major role in determining the strength of a meteorite and therefore its behavior in the atmosphere. (a) The Novato meteorite is essentially an impact breccia, a stony meteorite whose compressive strength has been greatly increased by a shock-produced glass that permeates the meteorite. (b) Similarly, many stony meteorites have been blackened and hardened by shock heating. (c) Iron meteorites are typically very tough and often pass through the atmosphere with little fragmentation, however even irons can have crystal faces that sometimes behave as lines of weakness which result in fragmentation. (d) The Chelyabinsk meteorite is typical of many, perhaps most, stony meteorites that have abundant cracks which greatly weaken the stone and cause considerable fragmentation in the atmosphere. (e) In the case of Chelyabinsk there are regions where black melt glass has permeated the stone. These hard clasts are easily separated from the rest of the meteorite and, while tough themselves, aid in the disintegration of the meteorite in the atmosphere by readily forming cracks along clast boundaries. (Image credits: Jenniskens et al., 2014; McKeever and Sears, 1980; Paul Withers, University of Manchester; Bob King, universetoday.com; James Tobin, meteorite.com).

5.4. Physical properties

The physical properties of meteorites have long been neglected; although Wood (1963) summarized the meager amount of data on porosity, compressive strength, acoustic velocities, density, magnetic susceptibility, specific heat, thermal conductivity, resistivity, dielectric properties, and reflectance, then available. Various authors discussing the atmospheric behavior of meteorites have determined certain parameters in a somewhat *ad hoc* way (Baldwin and Sheaffer, 1971; Ceplecha et al., 1993; Chyba et al., 1993; Hills and Goda, 1993; Ceplecha and Revelle, 2005; Popova et al., 2011). Starting in 1998 Guy Consolmagno has led a major effort to determine densities and porosities, utilizing the Vatican's major meteorite collection. The best and most recent review is a PhD thesis (Macke, 2010). Most recently, Consolmagno has turned his attention to heat capacity (Opeil et al., 2010, 2012; Consolmagno et al., 2013). Consolmagno and colleagues' work was focused on the scientific implications of the data and, in particular, the implications for the structure and low density of asteroids. Recent work performed in Russia indicates the complexity of strength measurements for meteorites, since composition, microstructure, and temperature, nature of the applied force, details of crack initiation, propagation and total fracture energy, fracture mechanism (e.g. ductile versus brittle) all affect strength (Grokhovsky et al., 2011), while data for compressive strength under ideal laboratory conditions is still scarce (Petrovic, 2001). Kimberley and Ramesh (2011) suggest that metal grains play a critical part in the fracture process of chondrites.

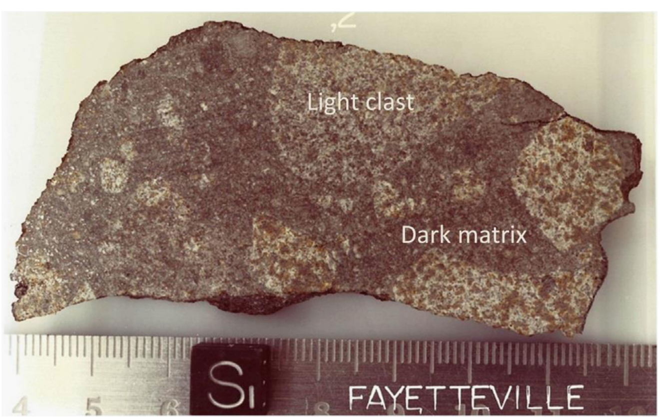

Fig. 10. A relatively small number of stony meteorites have a unique internal structure consisting of “normal” light clasts embedded in an unusual dark matrix which shows signs of being on the very surface of the asteroid. They are known as “gas-rich regolith breccias”. They are essentially true regolith that has been “lithified” by a shock sintering process which made it possible for them to come to Earth as meteorites. (From Schwarz and Sears, 1988).

5.4.1. Value of measurements of physical properties to the asteroid impact hazard effort

All theoretical models of meteoroid behavior in the atmosphere require the input parameters listed in Table 4. This list was drawn up after consultation with the entry engineers at Ames Research Center.

6. Conclusions: making the connection to the asteroid hazard

We have established a laboratory at the Ames Research Center whose focus is the characterization of meteorites from the perspective of the asteroid hazard. A major initiative is the establishment of a laboratory to measure the physical properties detailed earlier. Meteorites are in the process of being acquired and the first samples will process through the laboratory in the next few months. It is expected that since the amount of material needed for these measurements is much larger than most museum loans, samples will need to be purchased and this may limit the scale of the operation. The current plan is to make duplicate measurements for all but strength, where only one measurement will be made in view of sample demands.

Meteorites will enter the laboratory and move through a number of stations at which each parameter will be determined. Near the beginning of the cycle, subsamples will spall off to be sent to a laboratory equipped to measure tensile and compressive strength while other subsamples will go to Lawrence Livermore National Laboratory for additional measurements specific to their requirements for asteroid deflection. Microscopes are available to check the petrographic properties of the meteorites, to ensure they are representative of their class and note any cracks and shock effects that might influence the data. Another major thrust of the laboratory will be to document the fracture history of meteorites through a campaign of photographing and quantifying the fraction of meteorites that are heavily cracked with a view to working with Ames' reentry engineers to find ways to model the fracture process. The laboratory will collect and synthesize existing data and supplement these where obvious gaps are observed and it will conduct a systematic study of meteorites with special relevance to the asteroid impact hazard effort. The effects of weathering on existing data will be assessed by a study of Antarctic meteorites, recognizing that weathering processes will vary with climate, but detailed studies will be made on observed falls where weathering should be absent or minimal. The petrographic check will identify problems.

Finally, the question remains, how do we assimilate all the available data, the data from meteorites, from remote sensing of asteroids, and from numerical models of asteroids and atmospheric entry, into a form that addresses the two major aspects of the asteroid impact hazard effort, deflection and impact management? A website is being created to be developed by the Ames

Table 4
Physical parameters needed for entry calculations and current status[a].

Parameter	Example of paper reporting these data	Example of paper describing methods[b]
Bulk density	Rossi et al. (2008)	Britt and Consolmagno (2003)
Grain density	Tamari (2004)	Consolmagno and Britt (1998)
Compressive strength	Kimberley and Ramesh (2011)	Frew et al. (2001)
Tensile strength	Price and de Freitus (2009)	Wood (1963)
Acoustic velocity (longitudinal and shear)	Thomas (1970)	Flynn (2004)
Specific heat	Dilley et al. (2002)	Consolmagno et al. (2013)
Thermal conductivity	Dilley et al. (2002)	Opeil et al. (2010)
Thermal emissivity	Ruff et al. (1997)	Ashley and Christensen (2012)

[a] Comments: (i) Porosity is calculated from bulk density and grain density. (ii) Elastic moduli (Young's modulus and Poisson's ratio) are calculated from acoustic velocity.
[b] The methods described in column 3 are not necessarily the methods used by the authors in column 2

Research Center that takes data from existing or new databases and numerical models, looks for asteroid and meteorite matches, then assembles the data in an easily accessible form for the two applications, deflection and atmospheric passage. In this way, a potentially hazardous asteroid can be quickly assessed, missing data flagged, and the best available information presented automatically to world-wide users.

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