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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,