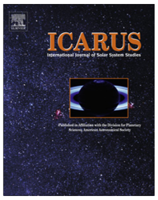
Icarus 266 (2016) 96–111

Contents lists available at ScienceDirect

Icarus

journal homepage: www.journals.elsevier.com/icarus



Orbital and physical characteristics of meter-scale impactors from airburst observations

P. Brown[a,b,*], P. Wiegert[a,b], D. Clark[c], E. Tagliaferri[d]

[a] Dept. of Physics and Astronomy, University of Western Ontario, London, Ontario N6A 3K7, Canada
[b] Centre for Planetary Science and Exploration, University of Western Ontario, London, Ontario N6A 5B8, Canada
[c] Dept. of Earth Sciences, University of Western Ontario, London, Ontario N6A 5B7, Canada
[d] ET Space Systems, 5990 Worth Way, Camarillo, CA 93012, USA

ARTICLE INFO

Article history:
Received 12 June 2015
Revised 23 November 2015
Accepted 23 November 2015
Available online 2 December 2015

Keywords:
Meteors
Near-Earth objects
Meteorites

ABSTRACT

We have analyzed the orbits and ablation characteristics in the atmosphere of 59 Earth-impacting fireballs, produced by meteoroids 1 m in diameter or larger, described here as meter-scale. Using heights at peak luminosity as a proxy for strength, we determine that there is roughly an order of magnitude spread in strengths of the population of meter-scale impactors at the Earth. We use fireballs producing recovered meteorites and well documented fireballs from ground-based camera networks to calibrate our ablation model interpretation of the observed peak height of luminosity as a function of speed. The orbits and physical strength of these objects are consistent with the majority being asteroidal bodies originating from the inner main asteroid belt. This is in contrast to earlier suggestions by Ceplecha (Ceplecha, Z. [1994]. Astron. Astrophys. 286, 967–970) that the majority of meter-tens of meter sized meteoroids are "… cometary bodies of the weakest known structure". We find a lower limit of ~10–15% of our objects have a possible cometary (Jupiter-Family comet and/or Halley-type comet) origin based on orbital characteristics alone. Only half this number, however, also show evidence for weaker than average structure. Two events, Sumava and USG 20131121, have exceptionally high (relative to the remainder of the population) heights of peak brightness. These are physically most consistent with high microporosity objects, though both were on asteroidal-type orbits. We also find three events, including the Oct 8, 2009 airburst near Sulawesi, Indonesia, which display comparatively low heights of peak brightness, consistent with strong monolithic stones or iron meteoroids. Based on orbital similarity, we find a probable connection among several events in our population with the Taurid meteoroid complex; no other major meteoroid streams show probable linkages to the orbits of our meter-scale population. Our impactors cover almost four orders of magnitude in mass, but no trend in height of peak brightness as a function of mass is evident, suggesting no strong trend in strength with size for meter-scale impactors consistent with the results of Popova et al. (Popova, O.P. et al. [2011]. Meteorit. Planet. Sci. 46, 1525–1550).

1. Introduction

The nature of the population of meter-scale impacting objects at the Earth is of considerable interest. The flux at meter-scales is responsible for delivery of many of the recovered meteorites at the Earth; indeed almost half of all the known fireball producing meteorites had initial meteoroid diameters in excess of 1 m (Borovička et al., 2015). Boslough et al. (2015) define an airburst as a bolide with total kinetic energy in excess of 0.1 kT TNT equivalent (where 1 kT TNT = 4.184×10^{12} J). Assuming an ordinary-chondrite-like bulk density (3700 kg m^{-3}) and mean impact speed of 20 km/s, this airburst definition corresponds to a size threshold for a spherical rock of 1 m diameter. Under these assumptions, this is the size at which meteoroid impacts transition into airbursts as defined by Boslough et al. (2015) and are at the lower end of where ground damage (e.g. from an iron meteoroid) might be expected. Such small near-Earth objects (NEOs), which are bodies orbiting the Sun having perihelion distances less than 1.3 AU, are also the target population of the proposed Asteroid Redirect Mission (ARM) (Brophy et al., 2012) and therefore of current practical interest.

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[*] Corresponding author at: Dept. of Physics and Astronomy, University of Western Ontario, London, Ontario N6A 3K7, Canada.

E-mail address: pbrown@uwo.ca (P. Brown).

http://dx.doi.org/10.1016/j.icarus.2015.11.022
0019-1035/

The origin and composition of NEOs at meter-scales may also provide hard constraints on the delivery and source regions both for meteorites and near-Earth asteroids or NEAs (the sub-population of NEOs which show no extended optical emission beyond a point-source) in general (e.g. Bottke et al., 2002); yet this NEA size regime remains poorly studied. There are less than 250 known NEAs having diameters below ~10 m ($H > 28$)[1] (from a total population estimated to be near 10^8 (Harris and D'Abramo, 2015)) emphasizing the scarcity of data at these small sizes. Physical data on such small NEAs is even less abundant; only ~5% of NEAs in this category have a known rotation period and only one (2008 TC_3 – the only asteroid imaged before impact, producing the Almahata Sitta meteorite) has detailed reflectance spectral information (Warner et al., 2009).

Recently, by combining thermophysical and non-gravitational force modeling, and using infrared measurements and high precision astrometry of two small NEAs (2009 BD and 2011 MD), Mommert et al. (2014a, 2014b) has been able to place constraining limits on size, bulk density and porosity of small NEAs for the first time. However, such model-based estimates have many free parameters and hence solutions for size/albedo/density are probabilistic in nature for each object. Nevertheless, Mommert et al. (2014a) conclude that the most probable parameters matching the infrared and kinematic behavior of 2011MD suggest it is a rubble-pile assemblage with a most probable bulk density of $600 < \rho < 1800\ \mathrm{kg\ m^{-3}}$. This is an important result as it remains unclear what fraction of meter-scale NEAs are rubble-pile assemblages or stronger monoliths (cf. Sánchez and Scheeres, 2014), a question intimately linked to the ultimate origin and evolution of this population.

An alternative method of probing small NEA structure is to observe their interaction with the Earth's atmosphere in the form of bright fireballs. A fireball is any meteor whose apparent peak brightness exceeds Venus ($Mv = -4$). In this technique, the ablation behavior of the object in the atmosphere provides clues to its internal structure, in particular its crushing strength, as the atmospheric stagnation pressure is assumed to equal the meteoroid crushing strength at points of fragmentation (e.g. Baldwin and Sheaffer, 1971). This technique, when applied to the suite of well observed meteorite-producing fireballs (a sample of about two dozen as of 2015) has shown that most such fireballs, while able to produce meteorites with high (tens to hundreds of MPa) compressive strength, are consistent with pre-impact meteoroids having relatively weak (~1 MPa or less) global strength (Popova et al., 2011). This observation has historically been interpreted to suggest most large meteoroids have extensive pre-existing collision-induced cracks (Halliday et al., 1989). None, however, show unambiguous evidence of fragmentation behavior at high altitudes corresponding to the very low-strengths which would be consistent with those expected of a true rubble-pile (where $\sigma < \sim hPa$; Sánchez and Scheeres, 2014). These meteorite producing fireballs, however, are a biased sample of all meter-scale objects colliding with the Earth, as they contained material strong enough to survive as meteorites (e.g. Borovička et al., 2015).

Ceplecha (1994) examined all fireball data then available and tabulated 14 fireballs which he estimated to have been produced by meteoroids with pre-atmospheric diameters in excess of 1 m. His primary conclusion was that the majority of these meter-scale impactors were weak bodies, likely cometary in nature. This is a surprising result given the lack of observations of a significant population of enduring small (~hundreds of meter) cometary nuclei (Fernández et al., 2013; Fernández and Sosa, 2012; Snodgrass et al., 2011) which should be detectable. Cometary fragmentation events do show short-lived small (decameter to hectometer) sized nuclei, but these persist for short periods before disappearing (A'Hearn, 2011). While some authors have claimed telescopic detection of meter to tens of meter-scale objects in meteoroid streams (Smirnov and Barabanov, 1997) these remain unconfirmed (Beech et al., 2004; Micheli and Tholen, 2015), with the lifetime of meter-scale volatile fragments in most major meteoroid streams estimated to be of order only one or a few revolutions (Beech and Nikolova, 2001). Among the NEA population, it is estimated from physical properties and orbital characteristics alone, that 8 ± 5% of the asteroid-like NEO population are cometary in origin (DeMeo and Binzel, 2008) while other studies suggest the fraction may be even lower (e.g. Tancredi, 2014). While these values are valid for larger (hundreds of meters to kilometer-scale) NEOs than our meter-scale population, if a true sudden change in population characteristics occurs somewhere in the tens of meters to hundred meter size range, it is potentially very revealing about source populations.

Here we examine the orbits and atmospheric behavior of a suite of 59 fireballs produced by meter-size (diameter >1 m) meteoroids in an effort to constrain their likely physical structure and origin based on ablation behavior and their orbits. As a 1 m sized object collides with the Earth roughly once every ~10 days (Brown et al., 2002a), large atmospheric area-time products are needed to have a significant prospect of collecting many such events. We make use of three data sources: long running ground-based optical surveys of fireballs, large meteorite producing fireballs and US Government Sensor observations of bolides.

2. Datasets and methods

We isolate meter-scale impactors based on their total preatmospheric kinetic energy. For reference, a spherical one-meter-in-diameter chondritic stone (which we assume has a bulk density near $3700\ \mathrm{kg\ m^{-3}}$ as an upper limit to the observed bulk density of all three ordinary chondrite classes (Britt and Consolmagno, 2003)) has a mass of ~1900 kg. For objects on typical NEA orbits, Earth impact speeds average ~20 km/s (Morbidelli and Gladman, 1998) which for a 1 m chondritic object corresponds to 3.8×10^{11} J or equivalently 0.09 kilotons (kT) of TNT equivalent (where $1\ \mathrm{kT} = 4.184 \times 10^{12}$ J). At the lowest speed for an Earth impactor (11.2 km/s – escape speed from the Earth) the energy is 0.03 kT while at 30 km/s the energy is 0.2 kT. Not knowing the bulk density for most of the events in our dataset (see later) we use this high chondritic density when density is unknown and round our diameter estimate to the nearest first decimal place. This produces a conservative estimate of size, making it unlikely we include smaller objects, but possibly removing a few borderline cases where the bulk density may be lower.

For our data, speeds are usually instrumentally measured with sufficient precision that the speed uncertainty represents a negligible source of error in the estimation of event energy. The determination of the mass is more problematic. In most cases, the radiation emitted by the bolide is summed over time and some integral luminous efficiency, τ, must be used to estimate true mass (and hence total energy) (see Borovička et al., 2015 for a detailed physical description). As summarized in Nemtchinov et al. (1999), earlier estimates of τ (e.g. Ceplecha and McCrosky, 1976) were based on experimental data from small (gram-sized) artificial meteoroids, resulting in $\tau < 1\%$ at speeds below 30 km/s. For meter-scale objects, the radiation emission becomes particularly complicated – theoretical estimates of τ for large, deeply penetrating bolides (in differing passbands) have been estimated by Nemtchinov et al. (1997), Golub' et al. (1996) and from experimental fits to fireball data by ReVelle and Ceplecha (2001). All of these

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[1] JPL Horizons – June 10, 2015.