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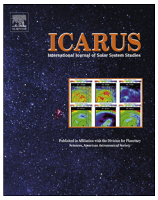

Modelling the brightness increase signature due to asteroid collisions

Ev McLoughlin *, Alan Fitzsimmons, Alan McLoughlin

Astrophysics Research Centre, School of Mathematics and Physics, Queen's University Belfast, University Rd, Belfast, Northern Ireland BT7 1NN, UK

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ABSTRACT

We have developed a model to predict the post-collision brightness increase of sub-catastrophic collisions between asteroids and to evaluate the likelihood of a survey detecting these events. It is based on the cratering scaling laws of Holsapple and Housen (Holsapple, K.A., Housen, K.R. [2007]. Icarus, 187, 345–356) and models the ejecta expansion following an impact as occurring in discrete shells each with their own velocity. We estimate the magnitude change between a series of target/impactor pairs, assuming it is given by the increase in reflecting surface area within a photometric aperture due to the resulting ejecta. As expected the photometric signal increases with impactor size, but we find also that the photometric signature decreases rapidly as the target asteroid diameter increases, due to gravitational fallback. We have used the model results to make an estimate of the impactor diameter for the (596) Scheila collision of $D = 49$–65 m depending on the impactor taxonomy, which is broadly consistent with previous estimates. We varied both the strength regime (highly porous and sand/cohesive soil) and the taxonomic type (S-, C- and D-type) to examine the effect on the magnitude change, finding that it is significant at early stages but has only a small effect on the overall lifetime of the photometric signal. Combining the results of this model with the collision frequency estimates of Bottke et al. (Bottke, W.F. et al. [2005]. Icarus, 179, 63–94), we find that low-cadence surveys of ~one visit per lunation will be insensitive to impacts on asteroids with $D < 20$ km if relying on photometric detections.

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1. Introduction

The main asteroid belt is collisionally dominated with large asteroids' shapes, sizes and surface geology controlled by impacts. Studies of collisions help us to understand the evolution of the shape of the asteroid population and in turn the formation of our Solar System. These studies may involve laboratory experiments, computer modelling or observational programmes.

The evidence for collisions can be seen indirectly in main-belt asteroid families (Cellino et al., 2002), asteroid satellites and binaries (Merline et al., 2002). It can also be seen directly in recently observed collisions (Snodgrass et al., 2010; Jewitt et al., 2011; Stevenson et al., 2012). There are three possible collisions observed to date. In 2009 the 120 m diameter Asteroid P/2010 A2 suffered a collision with a 6–9 m estimated diameter impactor (Snodgrass et al., 2010) (but see Section 4.4). In 2010 another asteroid, (596) Scheila (113 km diameter), was hit with a ~35 m diameter impactor Jewitt et al. (2011). The most recent potential collision involved the object P/2012 F5 (Gibbs), which like others was originally identified as a potential main-belt comet Stevenson et al. (2012). Events like the (596) Scheila collision should occur approximately every 5 years and collisions with asteroids <10 m even more often (Bodewits et al., 2011).

Several recent surveys are capable of detecting collisions and cratering events. For example, the Canada–France–Hawaii Telescope Legacy Survey was used to search for Main-Belt comets among 25,240 objects in 2003–2009 (Gilbert and Wiegert, 2010), the Thousand Asteroid Lightcurve Survey (924 objects) was conducted with the Canada–France–Hawaii Telescope in September 2006 (Masiero et al., 2009) and the Hawaii Trails project was conducted in 2009 (599 objects) (Hsieh, 2009). While none of the surveys mentioned above were specifically looking for main belt collisions, the methods used in search for main belt comets would have also revealed any collisional events. There are also current surveys fully or partly dedicated to discovering Near Earth Asteroids, such as Pan-STARRS 1 (Kaiser et al., 2002), the Lincoln Near-Earth Asteroid Research (LINEAR, responsible for discovery of P/2010 A2) (Stokes et al., 2000), the Catalina Sky Survey (Spahr et al., 1996) and the VST ATLAS survey (Shanks et al., 2013) that are all capable of detecting main-belt collisions.

Much work has been done in modelling the parameters (i.e. shape of debris, brightness, total ejected mass, impactor mass) of known observed collisions (Kleyna et al., 2013; Ishiguro et al.,

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* Corresponding author.
E-mail address: emcloughlin03@qub.ac.uk (E. McLoughlin).

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2011a; Holsapple and Housen, 2007; Housen and Holsapple, 2011); and hydrodynamic modelling of generalised collision (Benz and Asphaug, 1999). This work focuses solely on the magnitude change following an impact as it is most likely to be observable by optical telescopes. Rather than looking at a specific object in the main belt, the described model looks at what would be expected with generic asteroids.

2. Model description

2.1. Cratering physics

Our model is based on the work by Holsapple and Housen (2007), who provide a summary of scaling laws that allows calculation of crater size using properties of the target and impactor, based on the results of impact experiments. These laws can also be used to calculate the evolution of the ejecta dispersal and consequently estimate the amount of material ejected and increase in brightness following a collision. The decrease in magnitude of the target asteroid is going to depend on the amount of material that was ejected and whether it is optically thin or not.

At high impact speeds, transfer of the energy and momentum of the impactor into the target occurs over area on the order of impactor size, while the resulting crater usually exceeds this size by many times. It is therefore a reasonable approximation to assume that impact occurs as a point source. Using theoretical analyses of mechanics of crater formation, Holsapple and Housen showed that the crater and ejected material characteristics depend on the quantity $aU^{\mu}\delta^{\nu}$, where a is the radius, U is the normal velocity component of the impactor and δ is the density of the impactor; μ and ν are scaling exponents.

The scaling exponents depend on the material properties. Theoretical values of μ range from 1/3 to 2/3 (Holsapple and Schmidt, 1987) and are a measure of the energy dissipation by material; a more porous material can dissipate energy more effectively and will have a lower value of this exponent. Experimentally determined values of μ are ~0.55 for non-porous materials (e.g. rocks and wet soils), 0.41 for moderately porous materials (e.g. sand and cohesive soils) and 0.33–0.40 for highly porous materials (Holsapple and Schmidt, 1987). Experimental values for ν were found to be the same for all materials at around 0.4 (Holsapple and Schmidt, 1987). By selecting appropriate material scaling parameters for a given impact and inserting them into a general expression for the relationship between radii of involved objects and crater size, a reasonably accurate estimate of the crater size (as well as crater formation time and transient crater growth) can be made.

We now summarise how we use the previous studies in our calculations. Consider a spherical, non-rotating asteroid of radius r following an impact from an object with radius a at sub Earth point. The general form of equation for crater size R consists of strength and gravity term:

$$R = aK_1(\text{gravity term} + \text{strength term})^{-\frac{\mu}{2+\mu}} \tag{1}$$

where

$$\text{gravity term} = \frac{S_g a}{U^2}\left(\frac{\rho}{\delta_{\text{grain}}}\right)^{\frac{2\nu}{\mu}} \tag{2}$$

$$\text{strength term} = \left(\frac{Y}{\rho U^2}\right)^{\frac{2+\mu}{2}}\left(\frac{\delta_{\text{grain}}}{\rho}\right)^{\frac{\nu(2+\mu)}{\mu}} \tag{3}$$

Here K_1 is a scaling parameter (1.03, 1.17, 0.725 for sand/cohesive soil, wet soils/rock and highly porous material respectively; Holsapple and Housen (2007)), Y is the average strength of the target material, ρ is the grain density of target, $U = 5$ km s^{-1} (Bottke et al., 1994) is the normal velocity component, δ_{grain} is the grain density of the impactor, S_g is the surface gravity of the target asteroid with mass M and radius r, calculated as follows:

$$S_g = \frac{GM}{r^2} \tag{4}$$

Depending on the asteroid type, different values of bulk density (for calculation of target asteroid mass) and grain density (for calculation of ejected mass) are used. The values and their sources are summarised in Table 1. Bulk densities of C- and S-type asteroids were taken from weighted averages of corresponding subclasses as summarised in Table 3 of Carry (2012). Grain densities of C- and S-types are assumed to be the same as their most likely meteorite analogues (Britt et al., 2002). Density of D-type asteroids is approximated by bulk and grain densities of the Tagish lake meteorite (Zolensky et al., 2002; Izawa et al., 2010).

The range of material strengths used is presented in Table 2. The strength value selected in this study was varied for each taxonomic type to explore the relationship between the type, strength and the corresponding magnitude change.

The crater radius R calculated in this way has a corresponding mass M_{crater}:

$$M_{\text{crater}} = k_{\text{crater}}\rho R^3 \tag{5}$$

where the scaling factor k_{crater} is taken to be 0.75 for cohesive soils, 0.8 for wet soils/rocks or 0.4 for highly porous material (Housen and Holsapple, 2011).

As we are interested in the ejected mass, since it is only that which contributes to the observed magnitude change of the asteroid, the full crater mass will give an overestimate of brightness. The total crater volume is made up of a volume of ejected mass, a volume of the mass that is uplifted near the crater rim and a volume due to compaction. The fraction k_{ejecta} of the total crater mass that corresponds to ejected mass is of order 0.2–0.5 (Housen and Holsapple, 2011).

$$M_{\text{ejecta}} = k_{\text{ejecta}}M_{\text{crater}} \tag{6}$$

Throughout this work we assume k_{ejecta} of 0.3 as being most appropriate to asteroids.

2.2. Velocity shell model

We consider the ejecta leaving the asteroid surface after the collision event. For simplicity, we assume that the debris expands spherically outwards from asteroid, the debris with each velocity v_n forming a shell of radius r_s (see Fig. 1). Effects from rotation of the target or impactor are beyond the scope of the current model. Impact experiments show that there is no significant correlation between velocity and mass of the particles (Holsapple et al., 2002). Therefore, each velocity shell is taken to have the same particle size distribution described below, in Section 2.3. As our aim is to model observable brightening from Earth, we assume that the ejecta cloud is centred on the asteroid, as at early epochs the asteroid itself and the ejecta will be unresolved. We also assume that the brightness of the asteroid plus ejecta is measured through an aperture of fixed radius r_{ap} and centred on the asteroid. To obtain

Table 1
Average bulk and grain density of asteroids depending on taxonomic type.

Asteroid type	Bulk density (kg m^{-3})	Grain density (kg m^{-3})
C	1840 (Carry, 2012)	2710 (Britt et al., 2002)
S	2640 (Carry, 2012)	3700 (Britt et al., 2002)
D	1670 (Zolensky et al., 2002)	2770 (Izawa et al., 2010)

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