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Ejecta cloud from the AIDA space project kinetic impact on the secondary of a binary asteroid: I. mechanical environment and dynamical model

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An understanding of the post-impact dynamics of ejecta clouds are crucial to the planning of a kinetic impact mission to an asteroid, and also has great implications for the history of planetary formation. The purpose of this article is to track the evolution of ejecta produced by AIDA mission, which targets for kinetic impact the secondary of near-Earth binary asteroid (65803) Didymos on 2022, and to feedback essential informations to AIDA's ongoing phase-A study. We present a detailed dynamic model for the simulation of an ejecta cloud from a binary asteroid that synthesizes all relevant forces based on a previous analysis of the mechanical environment. We apply our method to gain insight into the expected response of Didymos to the AIDA impact, including the subsequent evolution of debris and dust. The crater scaling relations from laboratory experiments are employed to approximate the distributions of ejecta mass and launching speed. The size distribution of fragments is modeled with a power law fitted from observations of real asteroid surface. A full-scale demonstration is simulated using parameters specified by the mission. We report the results of the simulation, which include the computed spread of the ejecta cloud and the recorded history of ejecta accretion and escape. The violent period of the ejecta evolution is found to be short, and is followed by a stage where the remaining ejecta is gradually cleared. Solar radiation pressure proves to be efficient in cleaning dust-size ejecta, and the simulation results after two weeks shows that large debris on polar orbits (perpendicular to the binary orbital plane) has a survival advantage over smaller ejecta and ejecta that keeps to low latitudes.

1. Introduction

In this paper, we describe our study of the dynamics of ejecta produced by a hypervelocity impact on the secondary component of a binary asteroid. We consider the binary asteroid (65803) Didymos, which is the target of the Asteroid Impact & Deflection Assessment (AIDA) space mission project, a collaboration between ESA and NASA. This mission, which is under Phase-A study in both agencies until summer 2016, is composed of two components to be launched separately in 2020. The first component, the European Asteroid Impact Mission (AIM), will rendezvous with Didymos in spring 2022 and will characterize the secondary of Didymos (called hereafter *Didymoon*) by measuring its surface, subsurface, and internal properties (see Michel et al. 2016). The second component, the US Double Asteroid Redirection Test (DART) consists of an artificial projectile, 300 kg in mass, and equipped with a camera. It will perform a kinetic impact experiment on the secondary during Didymos' encounter with the Earth in late September/early October 2022 that will be observed both by AIM and by ground based observatories (see Cheng et al. 2016). The impact should produce a change in the orbital period of the secondary around the primary as a consequence of the momentum transferred by the projectile. AIDA will thus offer the possibility of detailed interpretation of the deflection measurement, and will allow for direct comparison with numerical modeling efforts (e.g., Jutzi and Michel 2014). The knowledge obtained by this mission, which will include vast insight into the asteroid-scale collisional process, will have important implications for our understanding of the collisional evolution history of the Solar System.

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AIM is slated to retreat to a distance safely away from the target (about 100 km) during the impact by DART, but is to return at close proximity for post-impact characterization. Therefore, it is important to investigate whether the debris ejected by the impact can pose any risk to the spacecraft, and, if so, to determine where in the vicinity of the target we might expect hazardous debris, and for how long it would last. Moreover, understanding the fate of ejected particles from a cratering event is important in order to determine the potential contribution of cratering impacts and their ejecta in the formation of regolith on asteroid surfaces, which, for Didymoon, is suggested to be mainly produced by thermal fatigue (Delbo et al., 2014).

The dynamics of the ejected fragments and smaller dust is complex, as it involves processes acting at very different scales (e.g., the orbital motion and inter-granular processes). It is influenced by the gravitational perturbations from the celestial bodies (including the Sun, the planets, and the two binary components), collisions between the debris and with the two binary components' surfaces, radiative forces from the Sun, etc.

Several studies have already been performed regarding the dynamics of interplanetary and impact-generated dust. For instance, Richardson (2011), Richardson and Melosh (2013), Richardson et al. (2007) studied the fate of ejecta produced by the Deep Impact mission on the comet Tempel 1. Richardson (2011) developed the excavation flow properties model (EFPM) that extends the distributed ejecta initial condition into a region far away from the crater, and shows the oblique edges of the ejecta plume. The EFPM is basically a tracer methodology, which tracks the ejecta plume with a series of individual tracer particles, drawing the dynamic envelope of the ejecta with the flight paths of these tracers. This model was then applied to study the evolution of ejecta from small impacts on both components of the binary asteroid 1999 KW4 system (Richardson and Taylor, 2015), using 1800 tracer particles. A comparable study applied to (433) Ida system was made by Geissler et al. (1996), in which they explored the escape and reaccretion of ejecta from the crater Azzurra with massless test particles. In that paper, the effects of significant parameters were first examined, then the fates of these particles were discussed in detail. Fahnestock et al. (2014) performed a first study of the ejecta dynamics produced by the ISIS kinetic impactor onto asteroid (101955) Bennu, which is considered originally to accompany the OSIRIS-REx space mission (Chesley et al., 2014).

A complete systematic analysis of the effects of the various processes that can act on the ejecta from a binary asteroid has never been performed. The aim of this work is to build an informative model to assess the probable orbits of the ejecta from the DART impact. This model can then be applied to other systems or to singleton asteroids. It can also be used for a more general study aimed at understanding what can be expected when a natural impact occurs on an asteroid, and whether its environment as well as its surface, can be affected by the presence and reaccretion of ejecta. The present paper concentrates on the mechanical environment of the ejecta and on the foundations of our modeling of the system dynamics. Section 2 describes the mechanical environment of the ejecta, while Section 3 presents our numerical method to compute the ejecta dynamics. Section 4 presents a first application to the binary asteroid Didymos, and Section 5 provides conclusions and perspectives.

2. Mechanical environment

The objective of this section is to analyze the effects of different forces felt by the particles of the ejecta cloud in the context of a binary system. These forces vary greatly and depend upon the trajectories relative to the binary system. As a quick sketch of the post-impact process, the ejecta will be launched from the impact site, followed by an expansion process, and eventually spread across a wide region around the heliocentric orbit of the binary system. From the perspective of an individual particle, three possible states are considered: I. Re-impact: the particle re-impacts on one of the two components of the binary system; II. Escape: the particle escapes away from the influence of the binary system; III. Stable motion: the particle is sent into a long-term stable orbit within the binary system. These states are defined to follow the ejection and to be valid within the time span of concern. And the ultimate fate could be different as a particle may be placed in a temporary orbit around the binary and eventually impact with a binary component or escape from the system. The magnitudes of the forces acting on an ejected particle are correlated with its evolutional path, and also with its physical properties such as its size and albedo. This section focuses on the mechanical environment of the ejecta cloud produced by an impact on the secondary of (65803) Didymos, at the epoch considered by the AIDA mission when the object is close to the Earth in Fall 2022.

2.1. Reference model of (65803) Didymos

Didymos will have a close approach to the Earth at perigee distance 1.07×10^7 km ($\sim$ 28 Lunar Distance). We assume the deflection date and time to be 2022/10/04 at 09:48:00 UTC (perigee time given by Objects), that the projectile equipped on DART is about 300 g, and that the impact speed is 6.25 km/s. The considered impact energy is not expected to cause full-scale geological changes (Michel et al., 2016). Consequently, we assume that there is no reshaping of the target and we model the two components of Didymos as rigid bodies.

Several physical and dynamical properties of the Didymos system have been derived from observations (Michel et al., 2016). Table 1 lists the parameters employed to build the numerical model of Didymos, within uncertainties. Note that among these properties, only the primary rotation period, the mutual orbital period, the mutual orbit separation, and the diameter ratio of the secondary to the primary are measured directly by observations. These properties are given priority when choosing the parameters for the model (see Michel et al. (2016) for detailed discussion). The retrograde solution to the mutual orbital orientation with respect to the heliocentric ecliptic J2000 (Scheirich and Pravec, 2009) is favored by the observations, and we assume the related constraint on the eccentricity $\leq 0.03(3\sigma)$. Then assuming that the primary is uniformly rotating around the principal axis that maximizes the moment of inertia, and that the inclination of the mutual orbital plane to the primary's equator is zero, we obtain the polar orientation of the primary in the Solar System, as shown in Fig. 1. The shape model of Didymos' primary, derived from combined radar and photometric observations (Benner et al., 2010; Pravec et al., 2006), is used in this study to evaluate the non-spherical perturbation due to the primary's gravity.

Our knowledge of the secondary is very limited. In particular, its mass, size, shape, and rotational state will not be known with high accuracy in advance of the AIM rendezvous. Although other formation scenarios cannot be ruled out (Jacobson et al., 2013; Pravec et al., 2010; Scheeres, 2007), comparative analysis shows that it was likely formed by reaccumulation of small pieces escaping away from the primary during YORP spinup (Walsh et al., 2012; Fang and Margot, 2012), and thus it may have a rubble-pile structure and be tidally locked due to high internal dissipation. For modeling purposes, we adopt the assumptions indicated by Michel et al. (2016), i.e., that the shape of Didymoon is a triaxial ellipsoid with axis ratios chosen based on observations of similar systems: $a_S : b_S : c_S = 1.56 : 1.2 : 1.0$ (the long axis is oriented to extend through the primary's center of mass, the short axis is oriented perpendicular to the mutual orbital plane, and no initial libration