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Ejecta cloud from the AIDA space project kinetic impact on the secondary of a binary asteroid: II. Fates and evolutionary dependencies

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ABSTRACT

This paper presents a quantitative study of the evolution of the ejecta cloud released from a hypervelocity impact on a binary asteroid. The Asteroid Impact & Deflection Assessment (AIDA) mission project in collaboration between NASA and ESA aims to perform an asteroid deflection demonstration, using a half-ton projectile that will perform a hypervelocity impact on the surface of the secondary of the binary near-Earth asteroid (65803) Didymos, called hereafter Didymoon. We performed numerical simulations of the post-impact dynamics of the ejecta cloud in the framework of the current mission scenario of AIDA. Our analysis relies on a classification of the orbits as a function of the ejecta fates, e.g., a collision with one of the binary components or the escape from the region of influence of the system. A grid search of launching sites of ejecta was defined over the globe of Didymoon, and considering a wide range of possible ejection speeds, we determined the dependency of ejecta fate on launching sites (projectile impact sites) and speeds. This range enables us to track all the complex cases that include different types of dynamical fates. The results reveal the detailed proportions of the ejecta that are either orbiting, escaping or re-accreting on the primary/secondary at the end of the considered timescale, as a function of the ejection speed, which allows us to explore the global characteristics of the ejecta dynamical fates. Two major mechanisms are found to be working broadly during the post-ejection evolution of the ejecta cloud: 1) ejecta on mean motion resonance orbits with Didymoon produce long-term quasi-periodic showers onto Didymoon over at least a couple of weeks after the projectile impact, 2) ejecta on non-resonant orbits produce a rapid and high re-accretion flux. This rapid and high flux occurs just once because ejecta on such orbits leave the system unless they experience a collision during their first encounter. For both mechanisms, swing-bys of Didymoon are found to occur. These swing-bys are a source of chaotic motion because the outcome of the swing-by is extremely sensitive to the ejecta initial conditions. Moreover, for all ejecta speeds, a zone free of ejecta is noticed to emerge around the mid-latitude zone of the celestial sphere about two months after the projectile impact. Also, the extent of this zone depends on the ejecta speed. For the second part of this study, we performed full-scale simulations of the ejecta cloud released from 6 hypothetical impact sites. To define the initial conditions of the ejecta based on cratering scaling laws, we considered two kinds of material composing Didymoon's subsurface and then combined a power-law size distribution of the ejecta with an ejection speed distribution. We find that the ejecta cloud evolution can be divided in two periods. It starts with a first violent period (<10 h) with fast re-accretion or ejection of the ejecta from the system. A second period is found to be more sensitive to the launching site than the first one. During this second period, ejecta will either re-accrete or being ejected from the system, depending both on their sizes and on their average survival time in close proximity of the binary components. There is thus a size-sorting effect dictated by the solar radiation pressure, which proves to be efficient to move out of the system the dust-size ejecta (<1 mm) for all considered launching sites and material types. On the other hand, the larger ejecta, being less or not affected by the solar radiation pressure, can survive longer in the system.

1. Introduction

An ejecta cloud is one of the most expected outcome of an asteroid impact mission, such as the AIDA space project in collabo-

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ration between the National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA). If funded for launch, AIDA will be the first kinetic impact deflection test. Its objectives are to demonstrate asteroid deflection with a hypervelocity impact on the secondary of the near-Earth binary asteroid (65803) Didymos (called hereafter Didymoon) and to characterize the dynamics and the physical properties of the system. The US component DART (Double Asteroid Redirection Test) mission is the kinetic impactor (Cheng, 2016), and the European component, called AIM, for Asteroid Impact Mission (Michel, 2016) will observe the outcome of the DART impact. Note that the original AIM design and objectives, as studied by ESA up to phase B1 until December 2016, was not approved for funding byESA Member States at the ESA Council at Ministerial Level of 2016. However, since there was an expressed interest of several ESA Member States for this mission, it was encouraged to study an optimised version of AIM called Hera, to be proposed at the next ESA Council of 2019. This version keeps the main objectives and is capable of providing crucial data for the interpretation of the DART impact (Michel, 2018). The impact is planned to take place in 2022 when Didymos is approaching the Earth as close as ~28 Lunar Distance (Rivkin, 2016), so that it can also be observed from ground based observatories.

AIDA will thus be the first large-scale artificial impact on a potentially hazardous binary Near-Earth Asteroid (NEA) with a measurable deflection effect (the impact could make a perceptible shift of Didymoon's orbit; see Cheng (2016) for details), and it provides a unique opportunity to study the cratering process, as well as to understand the ejecta dynamics based on realistic data, including the quantity of the ejecta, their ejection velocity and size distributions, and more importantly, the ejecta's life cycle as a function of these characteristics.

The ultimate fate of the ejecta released from a crater is a crucial information that has many implications in planetary science. For instance, there is an ongoing debate on the contribution of cratering to the formation of regolith on small asteroid surfaces. As one important outcome of the AIDA mission, the statistical behavior of ejecta produced by the DART impact will be analysed and used to improve the theoretical modeling of the impact process (Holsapple, 1983; Schmidt and Housen, 1987; Holsapple, 1993). Laboratory experiments have been performed for decades, which improved drastically our understanding of the impact process on actual geological materials, but the sizes of sample targets in these experiments, generally of the order of centimeters, are orders of magnitude smaller than the size of actual asteroids (Piekutowski et al., 1977; Piekutowski, 1980; Cintala et al., 1999). Scaling laws were developed based on dimensional analysis that indicate how multiple parameters of the impact process relate to each other if the experiment conditions change. Housen et al. (1983) constructed the basic formulas of mass and velocity distributions of the ejecta, and experiments were then conducted in order to obtain the empirical values of the constant parameters employed in the scaling laws (Housen and Holsapple, 2003; 2011). Several lately developed measuring techniques have been used to determine the unknown constants under different conditions (Schultz et al., 2000; Anderson et al., 2003) and for different physical regimes (Housen and Holsapple, 1990; Holsapple, 1994). However, it is still an open question whether these laboratory results can be successfully extrapolated to a collisional event at planetary or asteroid scale. In particular, it has been established that the strength and porosity of the target surface material relate to the size of the asteroid (Richardson et al., 2002). Moreover, Housen (1992) showed that the ejecta velocities decrease as the target strength decreases, which, as we will demonstrate in this paper, will largely govern the statistical behavior of the ejecta cloud, especially the proportions of escaping, orbiting and re-accreted ejecta. In brief, ejecta with a speed over a critical value will tend to escape directly, unless blocked by the asteroid body, and the rest of the ejecta will be temporarily trapped in cycling orbits around the asteroid(s), which can imply a more complex orbital evolution.

Dynamical considerations are technically unavoidable in the discussion of the ejecta fate. According to the mission scenario of AIDA, the complexity of the mechanical environment near the binary Didymos might be unprecedented in previous space missions (see a detailed discussion in Yu et al., 2017), especially for the low-speed ejecta that are fated to remain in the vicinity of the binary. Starting from an individual ejecta trajectory, several important factors must be considered, according to the situation. Firstly, the orbital motion is highly influenced by the peculiarities of the binary components in terms of shape, gravity and rotation when the ejecta is approaching the surfaces (Scheeres et al., 2000; Tricarico and Sykes, 2010). These quantities are currently uncertain and will not be known until AIM performs the in-situ characterization of Didymos. Secondly, the trajectories trapped in the neighborhood of Didymos evolve basically in the context of a Circular Restricted 3-Body Problem (CR3BP) that contains a variety of perturbations that take different forms. Some trajectories initialized closely in phase space may extend across a large space around the binary during a time corresponding to several orbital periods ($P_{orb} = 11.92$ hr) of the binary because their Lyapunov times are comparable or even smaller than this time (Lecar et al., 1992; Mikkola and Tanikawa, 2007). Thirdly, the perturbation forces acting on the ejecta are due to multiple mechanisms. Collisions between the ejecta are supposed to be dense in the excavating stage, and to become increasingly rare as the dispersion of the curtain increases. Yu et al. (2017) presented a survey of the mechanical environment and found that the solar tide and solar radiation pressure are two major forms that affect the month-long evolution of the ejecta cloud. An informative model was thus created by combining these refined physical processes and known / hypothetical properties of the binary system according to the observations. In fact, the orbital behavior of the ejecta cloud has barely been discussed so far at this sophisticated level. Richardson (2011) proposed the excavation flow properties model (EFPM), which was developed to track the fluctuation of the ejecta plume that is extended into a region far from the crater using a semi-empirical initialization. This model was first successfully applied to the Deep Impact Mission for a ballistic analysis of the ejecta plume, and further to determine the physical properties of Comet Tempo 1 (Richardson et al., 2007; Richardson and Melosh, 2013). The EFPM was also applied to track the ejecta motion from hypothetical impact sites on Didymoon, showing the distribution of escaping ejecta on the celestial sphere and of the accreted ejecta on the surface of the bodies (Richardson and O'Brien, 2016).

This paper, as the second one of the present series, applies our proposed numerical model to explore the fate of the ejecta in a systematic way, which will allow us to understand the behavior of the ejecta cloud over a wide range of parameters and draw some statistically meaningful interpretations. Section 2 describes the initialization of our ejecta grid on the surface of Didymoon, which aims at a broad examination of the fate dependencies on two key factors, the launching site (or projectile impact site) on the grid and the ejection speed. Section 3 presents full-scale simulations of the ejecta evolutions from 6 hypothetical projectile impact locations, considering two material types composing the ejecta to define scaling law material parameters as well as the major orbital perturbations in a 2-months timescale. Conclusions and a discussion of the results are presented in Section 4.

2. An atlas of the ejecta fate

The analysis of the fate of the debris ejected from an impact should not be only limited to what happens when the ejecta