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Resolution dependence of disruptive collisions between planetesimals in the gravity regime

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ABSTRACT

Collisions are a fundamental process in planet formation. If colliding objects simply merge, a planetary object can grow. However, if the collision is disruptive, planetary growth is prevented. Therefore, the impact conditions under which collisions are destructive are important in understanding planet formation. So far, the critical specific impact energy for a disruptive collision Q_D^* has been investigated for various types of collisions between objects ranging in scale from centimeters to thousands of kilometers. Although the values of Q_D^* have been calculated numerically while taking into consideration various physical properties such as self-gravity, material strength, and porosity, the dependence of Q_D^* on numerical resolution has not been sufficiently investigated. In this paper, using the smoothed particle hydrodynamics (SPH) method, we performed numerical simulations of collisions between planetesimals at various numerical resolutions (from 5×10^4 to 5×10^6 SPH particles) and investigated the resulting variation in Q_D^*. The value of Q_D^* is shown to decrease as the number of SPH particles increases, and the difference between the Q_D^* values for the lowest and highest investigated resolutions is approximately a factor of two. Although the results for 5×10^6 SPH particles do not fully converge, higher-resolution simulations near the impact site show that the value of Q_D^* for the case with 5×10^6 SPH particles is close to the expected converged value. Although Q_D^* depends on impact parameters and material parameters, our results indicate that at least 5×10^6 SPH particles are required for numerical simulations in disruptive collisions to obtain the value of Q_D^* within 20% error.

1. Introduction

It is generally accepted that planets grow in protoplanetary disks composed of dust and gas (e.g., Hayashi et al., 1985; Ida and Lin, 2004). The process of fine dust growing into a planet can be divided into several stages. The first stage is characterized by the accumulation of dust and the formation of planetesimals, which are typically 1–100 km in size (Safronov, 1969; Wetherill, 1980; Goldreich and Ward, 1973; Weidenschilling, 1980, 1984; Wada et al., 2007, 2008, 2009; Kataoka et al., 2013). In the next stage, planetesimals collide with each other and grow (Greenberg et al., 1978; Wetherill and Stewart, 1989; Kokubo and Ida, 1996). In the terrestrial planet region (inside the ice line), several tens of Mars-sized rocky protoplanets are formed. In the gas giant planet region, because there are so many icy planetesimals, very large icy protoplanets whose masses are several times that of Earth are formed. In the last stage of gas giant planet formation, such large protoplanets begin to rapidly capture the surrounding nebular gas. Ultimately, gas giant planets such as Jupiter or Saturn are formed. In the final stage of terrestrial planet formation, Mars-sized protoplanets frequently collide with each other, ultimately forming Earth-sized terrestrial planets (Chambers and Wetherill, 1998; Agnor et al., 1999; Genda and Abe, 2003; Kokubo and Genda, 2010; Genda et al., 2012).

Many collisions constantly take place during planet formation. If colliding bodies merge, collisions promote planet growth. However, collisions do not always promote growth. For example, in the stage of planetesimal formation, collisions between dust aggregates accelerated by turbulence in a protoplanetary disk can be so destructive that the dust aggregates break into fragments instead of growing (Weidenschilling, 1984; Wada et al., 2008). Additionally, the stage of protoplanet formation involves a similar problem. Once proto-

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planets become massive, their stirring increases the random velocity of surrounding planetesimals, and collisions between planetesimals become more destructive. As the fragments resulting from the destructive collisions between planetesimals are removed by rapid radial drift due to gas drag in the protoplanetary disk, the depletion of bodies accreting onto protoplanets stalls protoplanet growth (Inaba et al., 2003; Kenyon and Bromley, 2008; Kobayashi et al., 2010, 2011). Conversely, the radial drift of fragments resulting from destructive collisions accelerates protoplanet growth at a pressure maximum in the protoplanetary disk (Kobayashi et al., 2012). Therefore, the conditions of collisional destruction for planetesimals is very important in understanding planet formation.

Impact energy is presumed to greatly influence collision outcomes and is useful to estimate how destructive a collision is. If the larger colliding body, target, is much larger than the smaller one, impactor, the specific impact energy Q is given by $Q = E_{imp}/M_{tar}$, where E_{imp} and M_{tar} are the impact energy and the target mass, respectively. The impact energy E_{imp} is given by $E_{imp} = 0.5\, m_{imp}\, v_{imp}^2$, where v_{imp} and m_{imp} are the impact velocity and the impactor mass ($M_{tar} > m_{imp}$), respectively. The critical specific impact energy Q_D^*, which is the specific impact energy required to disperse the target in two or more bodies with the largest body having exactly half the mass of the original target (i.e., $M_{tar}/2$) after the collision, is often used to characterize disruptive collisions. The value of Q_D^* for planetesimals determines the timescales of the collisional evolution of planetesimal swarms and debris disks (e.g., Wyatt et al., 2007; Kobayashi and Tanaka, 2010), which are related to planet formation (Kobayashi and Lohne, 2014; Genda et al., 2015).

When m_{imp} is not much smaller than M_{tar}, Q_{RD}^* should be used instead of Q_D^* (e.g., Leinhardt and Stewart, 2012), because Q_{RD}^* includes the size effect of the impactor. However, in our all numerical simulations, m_{imp} is less than 2% of M_{tar} (see Section 2.2), which means that Q_{RD}^* is almost identical to Q_D^*.

Q_D^* has been investigated using various approaches: laboratory experiments (e.g., Housen and Holsapple, 1999; Holsapple et al., 2002; Nakamura et al., 2009), analytical or scaling methods (e.g., Housen and Holsapple, 1990; Mizutani et al., 1990), asteroid belt observations (Durda et al., 1998), and numerical calculations (Love and Ahrens, 1996; Melosh and Ryan, 1997; Benz and Asphaug, 1999; Leinhardt and Stewart, 2009, 2012; Jutzi et al., 2010; Jutzi, 2015). For large-scale collisions, such as collisions between planetesimals or protoplanets, numerical calculations have been powerful tools to investigate collision phenomena because direct experimental measurements of such collisions are difficult in the laboratory.

In the gravity regime (target radius $R_{tar} > \sim 1$ km), Q_D^* increases with R_{tar}. The value of Q_D^* in the gravity regime has been calculated by several numerical methods so far (Fig. 1). One frequently used method is the smoothed particle hydrodynamics (SPH) method (Love and Ahrens, 1996; Benz and Asphaug, 1999; Jutzi et al., 2010; Jutzi, 2015), which is a Lagrangian method used to solve fluid motion (e.g., Monaghan, 1992; Springel, 2010). The other methods are the two-dimensional Lagrangian hydrocode (Melosh and Ryan, 1997), the hybrid code of the Eulerian hydrocode and the *N*-body code (Leinhardt and Stewart, 2009, 2012), and direct *N*-body code (e.g., Leinhardt and Richardson, 2002; Leinhardt et al., 2012). Among these methods, there are variations in the value of Q_D^* for constant R_{tar} by up to a factor of 10, as shown in Fig. 1. Leinhardt and Stewart (2012) could explain the spread of Q_D^* among the previous data to some extend by applying the scaling laws of the impact conditions (mass ratio, impact velocity, and impact angle) and material properties (strength and density). However, among the SPH methods (Love and Ahrens, 1996; Benz and Asphaug, 1999; Jutzi et al., 2010), there are also variations in the value of Q_D^*, which seems to be caused by different physical properties and material parameters among these codes. The code developed by Love and Ahrens (1996) includes self-gravity but not material strength, whereas that by Benz and Asphaug (1999) includes material strength but not self-gravity. That by Jutzi et al. (2010) includes both self-gravity and material strength, but their parameters for material strength are different from those used in Benz and Asphaug (1999).

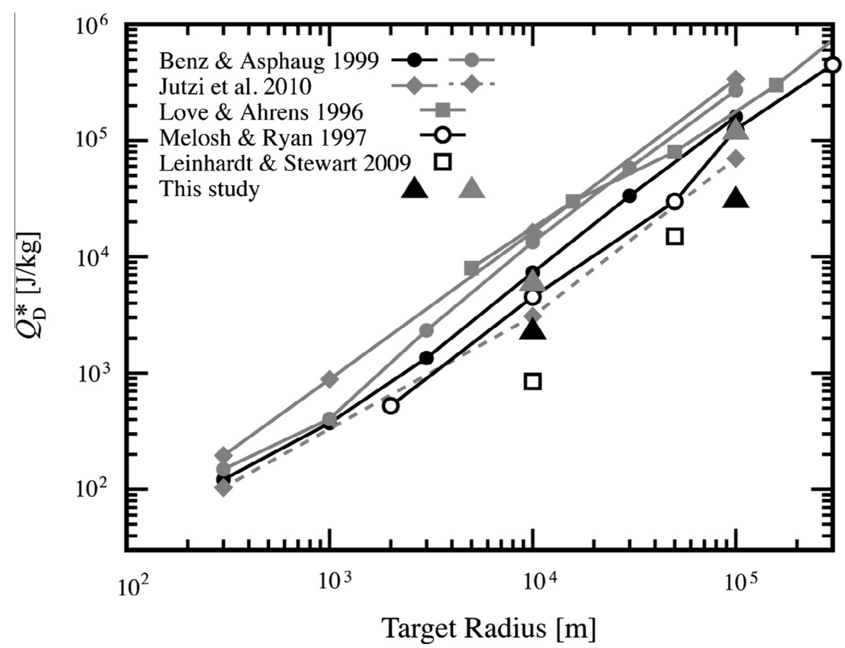

Fig. 1. Critical specific impact energy for disruptive collision Q_D^* for various target radii in the gravity regime calculated using several numerical methods. The results for collisions between basaltic objects (or granitic objects) are taken from the previous studies shown in the figure. Filled data points were obtained by SPH methods, and open data points by other numerical methods: the two-dimensional Lagrangian hydrocode (Melosh and Ryan, 1997) and the hybrid code of the Eulerian hydrocode and *N*-body code (Leinhardt and Stewart, 2009). Black and gray data points represent head-on and oblique (45°) collisions, respectively. Jutzi et al. (2010) considered target bodies with high (solid line) and low strengths (dashed line). Our results for the cases with the highest resolution (5×10^6 SPH particles) are also shown in this figure (for details, see Section 3.3).