Icarus 296 (2017) 91–98

Contents lists available at ScienceDirect

Icarus

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

Laboratory tests of catastrophic disruption of rotating bodies

A.J.W. Morris, M.J. Burchell*

Centre for Astrophysics and Planetary Science, School of Physical Sciences, University of Kent, Canterbury, Kent CT2 7NH, United Kingdom

ARTICLE INFO

Article history:
Received 10 October 2016
Revised 23 March 2017
Accepted 24 May 2017
Available online 26 May 2017

Keywords:
Collisional physics
Cratering
Impact processes
Asteroid
Rotation

ABSTRACT

The results of catastrophic disruption experiments on static and rotating targets are reported. The experiments used cement spheres of diameter 10 cm as the targets. Impacts were by mm sized stainless steel spheres at speeds of between 1 and 7.75 km s^{-1}. Energy densities (Q) in the targets ranged from 7 to 2613 J kg^{-1}. The experiments covered both the cratering and catastrophic disruption regimes. For static, i.e. non-rotating targets the critical energy density for disruption (Q^*, the value of Q when the largest surviving target fragment has a mass equal to one half of the pre-impact target mass) was $Q^* = 1447 \pm 90$ J kg^{-1}. For rotating targets (median rotation frequency of 3.44 Hz) we found $Q^* = 987 \pm 349$ J kg^{-1}, a reduction of 32% in the mean value. This lower value of Q^* for rotating targets was also accompanied by a larger scatter on the data, hence the greater uncertainty. We suggest that in some cases the rotating targets behaved as static targets, i.e. broke up with the same catastrophic disruption threshold, but in other cases the rotation helped the break up causing a lower catastrophic disruption threshold, hence both the lower value of Q^* and the larger scatter on the data. The fragment mass distributions after impact were similar in both the static and rotating target experiments with similar slopes.

1. Introduction

Impacts are a common evolutionary process for solar system bodies (e.g. see Osinski and Pierazzo, 2013 for a recent discussion). For large bodies, the impacts mostly alter the surface, but as bodies become smaller the risk increases of a catastrophic break-up of the target body. The presence of asteroid families in the asteroid belt (see Cellino et al., 2009, for a review), illustrates the outcomes of such break-ups when the energy injected into the system is not only sufficient to break the target apart, but also to disperse the fragments against their own self gravity.

To judge the likely outcome of an impact (cratering or disruption), a parameter is needed which scales with the sizes of the bodies involved. The energy density (Q) is therefore used, defined as the kinetic energy input by the impactor, divided by the total mass of the two bodies (m_p, impactor mass, and M_t, target mass). Since the mass of the target is usually significantly greater than that of impactor, the energy density is often taken as:

$$Q = \frac{m_p v_p^2}{2\ M_t} \tag{1}$$

This Q parameter is used extensively throughout the field of catastrophic disruption research. An alternative formulism for Q exists for planetesimal formation considerations in terms of reduced mass (Stewart and Leinhardt, 2009). This alternative adaptation of the energy density equation was to allow for the level of momentum transfer between the projectile and the target body being impacted, in the case where the projectile was comparable in size to the target. In the work here the impactor will be significantly smaller than the target, so the standard definition of Eq. (1) is used for Q.

The cratering regime of hypervelocity impacts onto targets is taken to apply for values of Q which result in the remaining mass from the target body being greater than 50% of the initial mass. At the 50% point in remnant mass, Q is known as Q^* and represents the start of catastrophic disruption. Strictly speaking there is a complication, as indicated above, concerning re-accumulation under self gravity. For very small bodies this is a negligible effect. But for bodies about 50 or 100 m in size, the extra energy needed to disperse the fragments of the shattered body adds significantly to Q^*. There are thus two target size regimes important in catastrophic disruption e.g. small sizes which are strength dominated (and where Q^* falls as target body size increases) and large sizes which are gravity dominated (where Q^* increases with body size). A review of this behaviour is given in Holsapple et al. (2002). This result is also shown in typical modelling results of catastrophic

* Corresponding author.
E-mail address: M.J.Burchell@kent.ac.uk (M.J. Burchell).

http://dx.doi.org/10.1016/j.icarus.2017.05.016

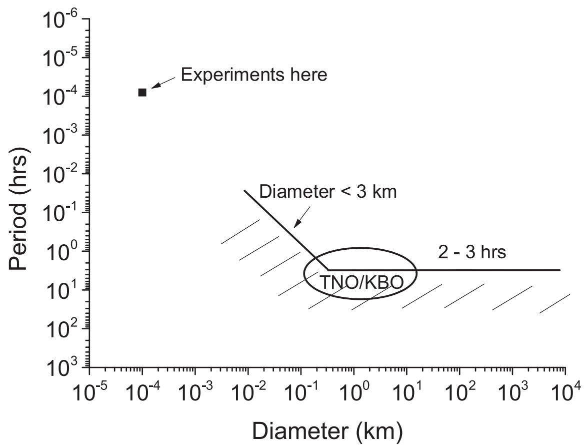

Fig. 1. Spin period vs. diameter for small bodies in the solar system (adapted from Fig. 1 in Holsapple, 2007). For asteroid diameters > 3 km the upper limit on the period is some 2 – 3 h, and for smaller sizes the period decreases. The periods of Trans-Neptunian Objects (TNO) and Kuiper Belt Objects (KBO) are also shown. The objects used in the experiments here (10 cm diameter, period 0.29 s) appear top left and can be seen to lie on the extrapolated trend line for small asteroids.

disruption such as the hydrocode work of Benz and Asphaug (1999) and the recent analytic model of Leliwa-Kopystyński et al. (2016).

However, despite the wealth of experimental and computational work into catastrophic disruption (e.g. Holsapple et al., 2002, and the references therein, and more recent work such as Granvick et al., 2016), one major aspect has remained untested experimentally, namely what if the target is rotating? All previous laboratory experimental work has used static targets. However, real solar system bodies rotate (see Fig. 1). The rotation rates of asteroids for example are well measured and the mechanisms behind asteroid dynamics are now widely studied, e.g. the YORP and Yarkovsky effects (see Bottke et al., 2006 for a review).

The question that arises is whether Q^* varies with rotational rate. Rotation effectively adds a stress into a body, indeed super-fast rotators may tear themselves apart. Given that many asteroids are held to be aggregate bodies and not monoliths, this is perhaps not too surprising. Recent modelling of catastrophic disruption of km-sized rotating bodies suggests the pre-impact rotation can play a role in the outcome of the event, reducing Q^* by around 6% (Ballouz et al., 2014,2015). However, earlier modelling of impacts on rotating rubble piles had suggested the pre-impact rotation did not influence Q^* significantly (Takeda and Ohtsuki, 2009).

The ability to refine theoretical and computational models on catastrophic disruption is of great importance, and therefore being able to make models as close to observations is key. It is thus important to undertake laboratory experiments to determine what happens in impacts on rotating objects. This is what is reported here.

2. Method

This work created hypervelocity impacts in the laboratory using a two stage light gas gun. The gun used was at the University of Kent and is described in Burchell et al. (1999). It fires a nylon sabot (discarded in flight) inside which is mounted a projectile which proceeds alone to the target. In this work the projectiles were stainless steel spheres, ranging in size from 1.0 to 2.5 mm diameter. The impact speed was varied from shot to shot (see Burchell et al., 1999, for a discussion of how this is done). In this work, the impact speed ranged from around 1 to 7.75 km s^{-1}, with most shots in the range 4 – 5 km s^{-1}, close to the 5 km s^{-1} estimated as the mean collisional speed in the asteroid belt (Bottke et al., 1994). The

Fig. 2. Cement sphere after manufacture.

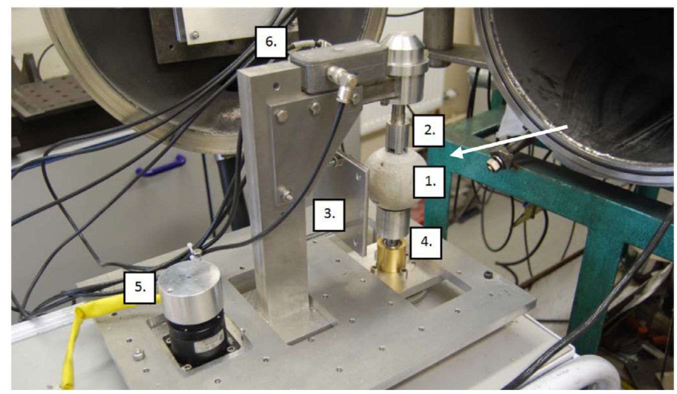

Fig. 3. The rotating target holder (made from aluminium) holding a cement target. Labels indicate: 1 - target, 2 – upper support, 3 – rear shield protect frame from impact ejecta, 4 – lower support, 5 – vacuum motor and 6 – electrical relays.

speed inside each shot was measured to better than ±1% by the projectile interrupting two laser light stations whilst in flight. Each laser was focussed on a photodiode, and the interruption in signal provided timing information which gave the speed. The target chamber was evacuated to around 0.5 mbar during each shot.

The targets used were cement spheres made in the laboratory. They were typically 10 cm in diameter, with each sphere measured and weighed before use. The typical mass pre-shot was 368 g and was measured to ±0.1 g. The cement (LaFarge Portland Cement) was mixed with water with a ratio of cement to water of 7:3. This ratio was varied in tests and found to produce the strongest cement samples after curing (in agreement with the work of Brandt, 1998). Care was taken to avoid formation of macroscopic voids during the casting process which poured the cement into spherical moulds. Tests on samples of cement cured in cylindrical moulds gave a compressive strength of 180 MPa and a tensile strength of 1.1 MPa. A typical target sphere is shown in Fig. 2.

To rotate the targets a device was made which held the sphere between two metal rods mounted vertically, spinning about the vertical axis running though the rods and the centre of the target. This is shown in Fig. 3. Since the rotating holder was to operate in the target chamber, a vacuum rated motor and set of electronics had to be used. The impact direction onto the target is shown with an arrow (in Fig. 3). The rotation frequency was set to be 3.44 Hz on average, i.e. a period of 0.29 s. In the experiments reported the median frequency was indeed 3.44 Hz, with a mean of 3.47 ± 0.11 Hz. This was chosen so that, combined with the target size, the experiments would correspond to the position shown on Fig. 1, which extrapolates from the period-sized relationship observed for small asteroids. The position of the targets was aligned