Icarus 247 (2015) 1–17

Contents lists available at ScienceDirect

Icarus

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

Landslides and Mass shedding on spinning spheroidal asteroids

D.J. Scheeres

Department of Aerospace Engineering Sciences, The University of Colorado Boulder, CO, United States

ARTICLE INFO

Article history:
Received 9 May 2014
Revised 5 September 2014
Accepted 10 September 2014

Keywords:
Asteroids
Asteroids, surfaces
Geophysics

ABSTRACT

Conditions for regolith landslides to occur on spinning, gravitating spheroidal asteroids and their aftermath are studied. These conditions are developed by application of classical granular mechanics stability analysis to the asteroid environment. As part of our study we determine how slopes evolve across the surface of these bodies as a function of spin rate, the dynamical fate of material that exceeds the angle of repose, and an analysis of how the shape of the body may be modified based on these results. We find specific characteristics for body surfaces and shapes when spun near the surface disruption limit and develop what their observable implications are. The small, oblate and rapidly spinning asteroids such as 1999 KW4 Alpha and 2008 EV5 exhibit some of these observable traits. The detailed mechanisms outlined here can also provide insight and constraints on the recently observed active asteroids such as P/2013 P5, and the creation of asteroidal meteor streams.

1. Introduction

The surface and interior geophysics of small rubble pile asteroids are not fully understood, yet are thought to play an important role in controlling the evolution of these bodies as a function of their spin rates and interactions with other Solar System bodies. This study focuses on one specific class of small asteroids, the spheroidal, rapidly spinning asteroids with an equatorial bulge. These bodies are strongly correlated to being a primary in binary asteroid systems, although they also appear frequently as solitary asteroids. The clearest example of this morphology is 1999 KW4 Alpha (Ostro et al., 2006; Scheeres et al., 2006), which has a pronounced equatorial bulge and a rapid spin rate, with the net gravitational and centripetal acceleration at its equator being near zero. Other well-known examples include Bennu (101955) (Nolan et al., 2013), the target of the OSIRIS-REx mission, and 2008 EV5 (Busch et al., 2011), the target of the formerly proposed MarcoPoloR mission.

In this paper the conditions for landslide failure of regolith on the surfaces of such asteroids are studied. In addition, the associated change in shape of such bodies and the fate of the disturbed regolith are evaluated. These predictions are compared with some known spheroidal-class asteroids to gain insight into the geophysics of such bodies. Also investigated are connections between surface slope failures on rapidly spinning bodies and the recent observations of "active asteroids", with multiple apparent shedding events occurring over a relatively brief time span (Jewitt, 2012; Jewitt et al., 2010, 2013; Hainaut et al., 2014). In this work we find, from a theoretical perspective, that these occurrences of mass shedding could be linked to the morphology of these spheroidal asteroids.

Our analysis strives for simplicity and thus mainly focuses on a minimal model that can appropriately represent the mechanics that occur for these bodies. Thus, for the shape we will primarily use a sphere. For the regolith properties, we will treat them as cohesionless grains with a specified friction angle that mantle a rigid sphere. For displaced grains undergoing plastic flow, we will make simple assumptions regarding how they will rearrange themselves, specifically assuming that they will preferentially arrange themselves into a flat distribution with zero slope. For the geopotential, we will assume that it can be modeled as a constant density sphere even after deformation. Finally, for grains that are released into orbit, we assume that unless specifically trapped by geopotential curves, that they will be subject to escape. The limitations of these different assumptions will be addressed in our discussions, although our theory will be constructed under their support. Finally, despite our simplified analysis we will also show some explicit computations for real asteroid shapes. These will help outline the limitations of our simplifications, and also show how our theory can be modified and extended to more realistic bodies.

There have been several hypotheses for how loose material can flow across the surface of an asteroid, with a particular emphasis on how equatorial bulges such as seen on binary asteroid primaries such as 1999 KW4 and on solitary spheroidal asteroids such as 2008 EV5 could have formed. In Guibout and Scheeres (2003) it was shown that as an ellipsoidal body spins more rapidly that

E-mail address: scheeres@colorado.edu

http://dx.doi.org/10.1016/j.icarus.2014.09.017
0019-1035/

the ultimate stable location for loose material to settle will always be at the equatorial region. Significantly, this occurs prior to the point where centripetal acceleration exceeds the gravitational acceleration, meaning that loose material is still bound to the surface. In terms of an ellipsoidal shape, the stability transitions between where loose material will settle depends on how the specific shape lies with respect to Jacobi and Maclaurin ellipsoids.

In Harris et al. (2009), they study a model with many similarities to the approach we take here. Some similar intermediate results and conclusions are drawn (and are identified later in the text), but ultimately that paper is more focused on the stability and form of static configurations. That paper does identify several hypotheses on how evolutionary spin-up effects can lead to certain configurations, some of which we review and analyze in more depth in the current paper. Minton (2008) studied the global shapes of bodies using a more advanced approach for the computation of self-consistent geopotentials for a fixed surface angle of repose. Both of these papers define tools that could be used in conjunction with the current study in future work to develop a consistent model for the deformation and flow of an asteroid surface.

Other papers have been more focused on the interpretation of existing shape models. In Scheeres et al. (2006), in the context of the shape of 1999 KW4 Alpha, several hypotheses were made on how that object could have gained its bulge. In addition to hypothesizing the surface flow of material to the equator, a hypothesis was made that the bulge could be formed from the in-fall of material that was initially placed in orbit about the body, and potentially driven back to the surface by the presence of the binary secondary body. Harris et al. (2009) made quantitative direct comparisons between the shape of 1999 KW4 Alpha and their computed radius profiles, pointing out the existence of mid-latitudes at nearly constant slope. More recently, Richardson and Bowling (2014) have studied the relaxation of asteroid surfaces covered with regolith, deriving a model that correlates body density with the observed slope profiles across a body's surface. The focus of that paper is to explain slopes in terms of erosional properties and their migration towards subdued static configurations. In contrast, a key aspect of the current study is to study systems that are on the brink of, or beyond, stability and are in the process of "falling apart."

There have also been investigations into related phenomenon that take a direct approach to the modeling of a body as a rubble pile. In Walsh et al. (2008, 2012) they model a proto-binary body as a collection of equal sized boulders and simulate its response as it is spun to high spin rates. In their simulations they saw the transport of boulders from the pole down to the equator where they would be flung off into orbit and contribute to the creation of a secondary. Using a different modeling technique Sánchez and Scheeres (2012) also explored the effect of friction and initial shape on the manner in which a rubble pile asteroid will deform and shed material. For both of these approaches, a limiting factor is that the rubble pile body components are essentially decameter sized boulders, and thus do not provide a high-resolution simulation of how centimeter sized and smaller grains would flow across the surface of an equivalently sized-asteroid. Jacobson and Scheeres (2011), using a simple model for asteroid fission and evolution, studied how the splitting of components and their subsequent evolution could lead to systems with a fast-spinning primary. A different line of investigations have been pursued in Fahnestock and Scheeres (2009), Harris et al. (2009), modeling the surface motion of particles on a spheroidal binary primary as perturbed by its secondary member. These studies have been more focused on how these interactions can cause a binary system to expand through the transfer of angular momentum. While relevant for the evolution of these bodies, the issues that are dealt with herein are more focused on the behavior of bulk materials, and not the system-wide response due to limited motion of surface grains.

There have also been studies that use continuum mechanics models to provide a global characterization of bodies with geophysical parameters appropriate for modeling regolith. Holsapple (2001, 2010) has studied the stability limits for self-gravitating, cohesionless ellipsoids characterized by a friction angle, using a Mohr–Coloumb failure criterion. Sharma has also studied the stability of such assemblages using tools from continuum mechanics (Sharma, 2012). Relevant for the current study, Hirabayashi (2014) modeled a rigid sphere mantled by a cohesionless regolith, showing that the existence of a more solid core postponed failure of the body. Comparison of results from Holsapple's study and our current work will show that for a body consisting entirely of cohesionless regolith, that global failure occurs at the same spin rate where surface slope failure occurs. The equivalence between these two failure theories is interesting, and drives an important assumption in our current model, which is that the asteroid is comprised of a rigid sphere mantled by cohesionless regolith up to a given depth. This is modeled in Hirabayashi (2014), where it is shown that the global failure limit of such a body will be at a faster spin rate than for a body which has a uniform distribution of regolith throughout.

Our current study is not fully distinct from any of these other studies, nor need it operate in isolation of these other effects. In many respects, the current work can be seen as an extension of the initial section of the Harris et al. (2009). The unique aspect of our current work is that it develops a more detailed and globally consistent prediction of how asteroid surfaces and sub-surfaces may be redistributed and lost from the surface given the basic mechanical forces acting in this peculiar environment. It is crucial to note that future missions and observations of these spheroidal asteroids will help resolve and clarify our understanding of how these bodies evolve.

The outline of this paper is as follows. We first review the relevant forces acting on a grain of regolith on, under and above the surface of a spinning body. This includes comparisons between a sphere and an oblate ellipsoid. Following this we introduce the geopotential of a body, with a definition that extends from the interior to the exterior region. Several useful concepts that can be derived from the geopotential are then introduced, such as "sea level" on a spinning body, altitude as a function of local slope and body shape, orbit equilibria above a spinning body, and the Roche Lobe. Also, several useful results on the volume beneath different radius and altitude profiles are derived. Then we discuss the granular mechanics of a regolith covered spinning sphere, identifying specific transition points where we would expect material to flow and redistribute itself across the surface. Next we discuss the possible orbital fate of such displaced material, in connection with the Roche Lobe on a spinning spheroid. Finally, we make applications of our results to realistic situations and asteroid models, distinguishing between different possible modes of asteroid failure, and discuss possible observable features that could be identified on the surfaces of bodies that have undergone such landslides as we describe. Connections between these events and active asteroids are also proposed and outlined.

2. The interior, surface and exterior environment on spinning spheroids

First define the environment above, on and below the surface of a sphere of radius R and surface gravity g_0, spinning about a fixed axis with an angular rate ω. Assuming rotational symmetry, define an equatorial axis $\hat{\boldsymbol{x}}$ and a polar axis $\hat{\boldsymbol{z}}$, and measure the location of a particle about the body by a radius r and latitude δ, measured