Planetary and Space Science 122 (2016) 88–93

Contents lists available at ScienceDirect

Planetary and Space Science

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

Interfacial Tension-Driven Differentiation-(ITDD) may result in a low-density central region inside kilometer-sized bodies

Francisco J. Arias *

University of Cambridge, Trumpington Street, Cambridge CB2 1PZ, United Kingdom

ARTICLE INFO

Article history:
Received 2 October 2014
Received in revised form
14 October 2015
Accepted 14 January 2016
Available online 28 January 2016

Keywords:
Microporosity
Differentiation
Rubble-pile model
Low-density central region
Small kilometer-sized bodies
Interfacial Tension-Driven Differentiation-(ITDD)

ABSTRACT

Interfacial Tension-Driven Differentiation, (ITDD), and its possible significance with regards to the interior structures of kilometer-sized bodies is discussed. Using a simple physical and geometrical model, an analytical expression for the conditions in which ITDD can occur is derived. It is shown that ITDD coupled with internal convection can lead to a counterintuitive result: that central regions may be less dense than outer regions in km-sized, initially melted bodies. ITDD offers an alternative explanation to the formation of microporosity inside of small bodies, (e.g. Churyumov–Gerasimenko-like objects), as well as macroporosity, which is suggested to occur in the interior of Mars' larger satellite Phobos, without recourse to rubble-pile models. Depending on the development of the velocity boundary layer at the solidification front, ITDD allows not just the possibility of central porosity, but also more complex scenarios, such as the formation of internal porosity rings.

1. Introduction

In planetary science, differentiation is the process of separating out different constituents of a planetary body as a consequence of their physical or chemical properties. This process leads to the development of compositionally distinct layers, where denser materials sink to the center of a planet, while less dense materials rise to the surface (e.g., Lissauer and de Pater, 2013). Other processes may be responsible for segregating layers, such as chemical differentiation driven by chemical affinity (which only happens locally, e.g., Lissauer and de Pater, 2013), or thermal differentiation driven by thermal gradients. The latter are also referred to as thermophoresis, thermomigration, or the Soret effect, where all require strong thermal gradients generally not achieved in bodies larger than 1000 m in size (although this process drives differentiation in magma chambers).

All in all, in planetary differentiation we have the following considerations:

1. Gravity-driven differentiation suggests that density increases toward the center.
2. However, there are some bodies for which the density seems to decrease toward the center: e.g., the asteroid Itokawa, (Abe et al., 2006), the comet Churyumov–Gerasimenko (Altwegg et al., 2015), and the 25–30% central porosities measured for Phobos (Pätzold et al., 2014), and possible other rubble-pile objects.
3. Current models that describe a decrease in central density do not rely on gravity-driven differentiation, but instead are explained by rubble-pile models, (e.g., Leliwa-Kopystynski and Kossacki, 2000) and outgassing models (e.g., Prialnik and Merk, 2008).

In rubble-pile models, chunks of rocks accrete haphazardly, leaving interior pockets and voids that are preferentially located in central regions. Therefore, such models preclude a molten origin. An interesting application of rubble-pile models is their application to Phobos. Nowadays, it has been proposed that the central porosity of Phobos (25–30%.) is due to the rubble-pile mechanism (Rosenblatt, 2007). However, a highly porous asteroid, if that is what Phobos once was, would probably not have survived being captured by Mars' gravity. Other times, small bodies feature a surprising homogeneity in porosity (e.g., Consolmagno et al., 2008), which could be difficult to convey via the random gravitational-aggregational mechanism.

Thus, it is worthwhile exploring the possibility of other types of mechanisms that could allow for the presence of low-density central regions (including porosities) in small bodies but considering an initial liquid state. In this work the possibility of other kind of differentiation (non-gravitational) from initial molten objects is investigated. The mechanism which is not driven by gravity may result in a low-density central region inside the body, and then justify the formation of central porosities starting from molten objects.

* Tel.: +32 14 33 21 94.
E-mail address: fja30@cam.ac.uk

http://dx.doi.org/10.1016/j.pss.2016.01.010

Nomenclature

a	radius of the particle, m
d_0	distance of adhesion, m
g	acceleration due to gravity
h	particle-solid melt separation distance, m
F	force, N
ΔF_{adh}	free energy of adhesion, J m^{-2}
Δh	volumetric latent heat, J m^{-3}
h_t	heat transfer coefficient, W m^{-2} K^{-1}
ΔT	subcooling temperature, K
$\mathbf{G}$	gravitational constant, m^3 kg^{-1} s^{-2}
Nu	dimensionless Nusselt number
R	distance from the center of the body to the front of solidification, m
Ra	dimensionless Rayleigh number
s	distance of front of solidification, m
t	time, s
T	temperature, K
V	velocity, m s^{-1}

Greek symbols

α	thermal diffusivity, m^2 s^{-1}
β	thermal expansion coefficient, K^{-1}
δ_v	thickness of the velocity boundary layer, m
ϕ	dimensionless factor for boundary effects in solidification rate
γ	surface tension, J m^{-2}
λ	latitude, (radians)
μ	dynamic viscosity, m^2 s^{-1}
ν	kinematic viscosity, kg m^{-1} s^{-1}
κ	thermal conductivity, W m^{-1} K^{-1}
ρ	density, kg m^{-3}
$\overline{\rho}$	average density celestial body, kg m^{-3}
Ω	rotational velocity, s^{-1}

Subscripts, Superscripts

cr	critical value
D	drag force
G	gravitational force
R	repulsive force
Ω	centrifugal force
p	particle
adh	adhesive
l	liquid
s	solid
D	drag
p	particle
ps	particle–solid
pl	particle–liquid
sl	solid–liquid
so	solidification

This paper is divided into four sections. In Section 2, the core idea of ITDD is presented and the theoretical background is derived. In Section 3 we present our results and discussion, while in Section 4 we summarize our conclusions.

2. Analytical model

2.1. Interactions between particles and solidification fronts

Consider an initial molten km-sized body starting to cool. This initial molten state may result from several classical mechanisms, e.g., collision events or radiative heating. Cooling results in a solidification front that propagates inwards over time.

As the solidification front passes through the cooling material, it can either segregate (i.e., reject or push along) or engulf material particles.

Thermodynamically, the process of particle rejection or engulfment by the solidification front, which is a constant-temperature, con stant-volume process, can be quantified by the net Helmholtz free-energy change of the system (i.e. the front of the solidification–particle–liquid).

The net free energy change per unit surface area for the adhesion process is given by Dongqing and Wilhelm (2010):

$$\Delta F_{adh} = \gamma_{ps} - \gamma_{pl} - \gamma_{sl} \tag{1}$$

where γ_{ps}, γ_{pl} and γ_{sl} are the particle–solid, particle–liquid and solid–liquid interfacial tensions (in J m^{-2}), respectively.

Thermodynamically, the condition for particle engulfment is given by

$$\Delta F_{adh} < 0 \tag{2}$$

and if ΔF_{adh} is positive, that is,

$$\Delta F_{adh} > 0 \tag{3}$$

there will be particle rejection, i.e. the segregation of particles due to the motion of the solidification front.

Let us consider the physical model depicted in Fig. 1, in order to balance the forces at the system front of the solidification–particle–surrounding liquid. Here, we assume that the relative density of the particle is lower than that of its surroundings. For example, the particle can be a gas bubble. The repulsive force, F_R, acting

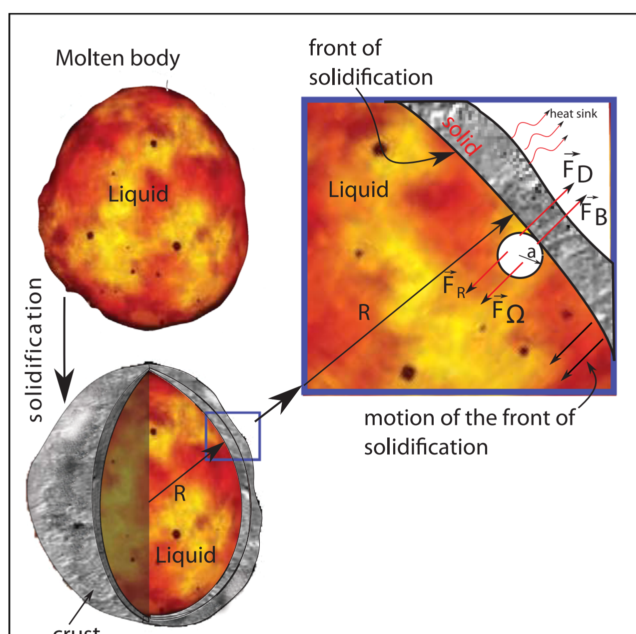

Fig. 1. Physical model of the motion of a solidification front and the resulting forces. Depicted here is the moment when the solidification front encounters a particle, and cooling is assumed to occur via radiative transport.