IMPACT COOLING OF A MAGMA OCEAN; C.A. Peterson, Hawaii Institute of Geophysics and Planetology, SOEST, University of Hawaii, Honolulu, HI 96822

INTRODUCTION

It has long been understood that hypervelocity impacts into planetary bodies produce deeply buried heat in targets. During planetary accretion, enough heat may accumulate to partially melt the growing body. However, most models of impact heating consider only the case of impact into a solid target. If a magma ocean existed on the Moon, impacts into it certainly occurred. Ejecta from such impacts would have been hot and would have been able to radiate some energy away into space. In addition, the temperature and fluid state of the target would have affected the partitioning of energy from the impact in as yet undetermined ways. Furthermore, impacts through a developing quenched crust or flotation crust would have accelerated radiative heat loss both through disruption of the insulating crust and by deposition of hot ejecta on top of the crust.

IMPACT HEATING AND COOLING

Discussions of the heat budget related to impact processes usually focus on the heat deposited into the target by the transformation of kinetic energy into heat upon impact. In most models of heating during planetary accretion [e.g., 1], ejecta is considered to have only a minor role; the ejecta may be heated to varying degrees, but remains on or near the surface and, except when accretion is rapid enough to quickly bury it, quickly radiates most of its excess heat away. Only the deeply buried heat really counts.

Seldom considered is the case of an impact into a silicate melt, such as the magma ocean hypothesized to have existed early in the Moon's history. In this case the ejected material begins its trajectory as molten rock, and during its ballistic flight it may be able to radiate away a significant amount of heat energy. For a very hot melt, one near its vaporization temperature, little heat could be added to the system; increased temperature would simply result in vaporization. Moreover, such a hot melt would be able, when ejected ballistically, to radiate away even more energy during its flight (proportional to T^4) than would a melt at liquidus temperature. The result: impact cooling of a (very hot) magma ocean.

Under some conditions, then, impacts may be expected to have a net cooling effect on a target. The limits of those conditions are yet to be determined, and while radiative heat loss from molten ejecta must certainly affect the degree of heating which occurs upon impact, it is not certain that there exists a realistic set of conditions under which net impact cooling would take place simply by radiative heat loss during ballistic ejection of magma. For example, if a 1 km projectile struck the Moon at 20 km/sec and created a parabolic transient crater with a diameter of 10 km and a depth of 3 km, the ejecta from that crater would have to cool by an average of several hundred degrees in order to radiate away an amount of heat equivalent to the kinetic energy of the impactor. While that seems unlikely, a definitive answer awaits development of a model which would quantify the net heating or cooling effect of impacts under a variety of conditions. A necessary first step in the development of such a model is to define the most important parameters affecting the heat budget during impacts into molten silicate targets in order to begin to constrain the conditions under which impact cooling might be an important process.

HEAT BUDGET

The heat budget for an impact may be divided into three phases. First, energy is added to the target by the impactor. Next, this energy is partitioned. Finally, heat is transferred through and/or out of the system. The degree to which these phases are understood varies.

Energy input: This phase is simple and well defined. The kinetic energy of the impactor is almost completely transferred to the target upon impact. $K=(1/2)mv^2$, where K is kinetic energy, m is mass, and v is the relative velocity at impact.

Energy partitioning: Melosh [2] estimates that up to 50% of the kinetic energy of a large (>10 km) impactor may be transformed into deeply buried heat during the impact. Eventually, of course, nearly all of the energy is transformed to heat (except when ejecta is energetic enough to escape the gravity well of the target) as the ejecta falls back and oscillations created by the impact damp out, and as energy absorbed by phase changes (e.g. vaporization) is released by the reversal of such changes (e.g. condensation). Nevertheless, the initial partitioning of energy into heat and kinetic energy of the ejecta is important because radiative cooling will be most effective for small particles (high surface-area-to-volume ratio) and those which spend the most time at the greatest distance from the surface of the target body. As ejecta falls back, the secondary impacts may provide additional ejecta with potential for radiative cooling.

Impacts into silicate melts are clearly different from those into crystalline material since no permanent crater results. The fluid nature as well as the temperature of the target may have significant effects on the partitioning of impact energy and must be carefully modeled. Gault and Greeley [3] have shown that the continuous ejecta blanket of a fluidized target (mud) extends further from the crater than is the case with crystalline targets. They have also shown that an impact into water, a very low viscosity target, produces a (larger) hemispherical transient crater cavity rather than the paraboloid of revolution found in solid targets [3]. In addition, it is reasonable to assume that more vapor would be produced by impact into a molten target than into a solid one. This would tend to carry away more of the energy that would otherwise be deposited into the target as heat. (Melt production is a meaningless term in this context.) This combination of less heat put into the target and more ejecta available to radiate heat away may significantly affect the heat budget of an impact.

Heat flux: A magma ocean would already be radiating heat away to space before the impact occurred. Additional radiative heat loss would occur due to the increased surface area created by excavation of the ejecta. Not all of the radiant energy would be lost to space; much would be directed back toward the target body. Any model of impact-related heat budgets must consider the morphological characteristics of the ejecta and sum the radiation absorbed and emitted by the ejecta and the target body.

DISCUSSION

Initial conditions in the target may be divided into two broad categories: the magma ocean may have a crust or it may not. Where there is no crust, most of the radiative cooling which results from an impact must occur during the ballistic flight of the ejecta. However, where a crust thick enough to support some or all of the ejecta, yet thin enough to be penetrated by the projectile, is present, radiative cooling may be enhanced in at least two ways. The ejecta can continue to cool after emplacement on the crust, and the impact will produce a hole in the crust through which heat may be radiated from the magma ocean.[4] Sasaki [5] has calculated that disruption of the crust would, by itself, result in a net cooling at mass accretion rates less than one Earth mass per 10^9 years.

O'Keefe and Ahrens [6] have developed a detailed model of energy partitioning in impacts using Eulerian finite-difference methods and considering phase changes and thermodynamic properties of silicates. Such a model could be extended to cover the case of impacts into molten silicate material. Important parameters which should be varied include: flux, size, impact velocity, and density of the impactors; temperature and viscosity of the target; morphology of the ejecta curtain; growth of a quenched crust on the ejecta; thickness and thermal conductivity of the magma ocean crust; mechanical strength of the crust; and foundering of a quenched crust after varying periods of time.

A model of this sort may be able to place some constraints on the evolution of a magma ocean once it has formed. If impacts can lead to cooling, then traditional notions of accretional heating may need to be rethought.

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