CRATERING BY IMPACT EJECTA, FROM MERCURY TO THE ASTEROIDS. E. B. Bierhaus[1] and L. Dones[2], [1]Lockheed Martin Space Systems Company (edward.b.bierhaus@lmco.com), [2]Southwest Research Institute (1050 Walnut St, Suite 300, Boulder CO 80302).

Overview: This analysis examines the relative populations of secondary craters in the inner solar system. Using a combination of "first principles" for cratering, in conjunction with modern scaling laws, we find that Mercury should have a significant population of secondary craters, perhaps more than any other body in the Solar System. The Moon and Mars should have similar populations of secondary craters, though the Moon should have more than Mars. And while their contribution is small, a non-zero population of secondaries will exist on the largest asteroids, such as Ceres and Vesta – those with escape velocities greater than perhaps 250 m/s.

Introduction: Primary craters – caused by the direct impact of asteroids or comets onto a solid surface – eject chunks of that surface, often at sizes and speeds sufficient to make additional craters. Craters made by these ejecta are known as secondary craters. Because cataloguing the size-frequency distribution of *primary* craters is the most common means to evaluate the age(s) of surfaces for which we do not have samples of known provenance (everywhere except the Moon), it is imperative to understand the contribution of the secondary population. The number and distribution of secondary craters has been in debate since analysis of the lunar surface in the 1960s. This topic has received significant attention in the last ten years because of the new wealth of high-resolution imagery from a variety of planetary surfaces. Definitively identifying all secondary craters is not yet feasible because distant secondaries can resemble small primaries, and because global crater measurements at scales relevant to secondary cratering are impossible either due to lack of sufficient image data for some objects, or the amount of labor involved for other objects. For these reasons (and others), most studies have examined specific secondary crater fields and extrapolated those effects to the global scale.

The purpose of this discussion is to bound the effect of secondary cratering by a combination of a "first principles" approach, in conjunction with a modern understanding of cratering physics. The debate regarding the extent of secondaries exists for all cratered surfaces, but has received the most attention for the Moon and Mars, mostly due to the vast amount of image data available for those two bodies. Our analysis here includes the Moon and Mars, as well as Mercury and Vesta, due to ongoing missions and the present and near-future availability of imaging data to test these calculations.

First Principles: For a given-sized primary impactor, there are a few key physical parameters that largely dictate the role of ejecta in adding to the crater population. These include: the primary impactor speed (v_i) and target surface gravity (g), which determine the size of the crater; and target escape velocity (v_{esc}), which sets how much of the fast moving ejecta escapes the target body. See Table 1 for the bodies we consider. We include the tidal effects of the Sun to calculate v_{esc}, but the difference between the value used here and the classical escape velocity is generally only ~1%.

A new parameter, introduced by [1] in application to icy satellites in the outer solar system, is the minimum velocity required to make a secondary crater (v_{min}). The idea is simple: at low velocities, an ejectum can land intact, or largely intact, as a boulder. At faster impact speeds, the ejectum disaggregates at impact but may not form a crater. At yet faster impact speeds, the ejectum will hit with sufficient energy to make a secondary crater. Analysis of boulders around lunar craters [2,3] indicates that the maximum ejection velocity for which a boulder survives intact is around 200 m/s. Secondary craters may form at speeds of 250 m/s, the value used for v_{min} here.

In reality, v_{min} likely spans a small range of values depending on the compactness of the ejecta cluster and the specifics of the mechanical strength of the target surface. However, using a single value for simplicity will not change the fundamental conclusions.

Table 1. Object Parameters

Object	v_i *[km/s]*	*g [m/s]*	v_{esc} *[km/s]*
Moon	19.7	1.6	2.3
Mars	7.0	3.7	4.2
Mercury	40	3.7	5.0
Vesta	5	0.2	0.3

Crater Scaling Laws: A recent update to the crater scaling laws [4] includes a comprehensive analysis of laboratory test results, synthesizing them with the extensive historical record of analytical efforts to describe crater formation. We use those scaling laws to estimate transient crater diameter, total mass ejected (m_{tot}), and mass available to make secondary craters (m_{sec}), for a 1-km diameter asteroid impactor. We use a 1-km asteroid because: *(i)* it is large enough to generate enough ejecta to make an observable population of secondary craters, and *(ii)* impacts of such bodies are frequent on geologic time scales.

Discussion: Figures 1 and 2 show m_{sec} (the mass available to make secondary craters) and f_{sec} (the fractional mass available to make secondaries, m_{sec}/m_{tot}), respectively. The calculations utilize gravity-scaled cratering from [4], assume a 1-km asteroid, and the parameters given in Table 1. Table 2 lists the transient crater diameter (D_t) on each body, as well as m_{sec} in terms of the impactor mass (m_{sec}/m_i).

Mercury. A clear conclusion from the analysis is that Mercury will express the most significant secondary population of the inner Solar System. And it exceeds those in the Jovian system, see [1], suggesting Mercury likely has the most significant secondary population in the Solar System. This is due to the very high primary impact speed(s), which generate significant amounts of fast moving ejecta, and the high escape velocity, meaning much of the ejecta are retained to make secondary craters. This prediction is borne out by observations of crater populations seen in MESSENGER image data [5,6].

Moon. Although the Moon is less efficient at holding on to fast moving ejecta than Mars (due to the lower escape velocity), the faster mean impact speed (and the lower surface gravity) means that a given impact will generate a larger crater. This does two things: *(i)* generates more ejecta per impact, and *(ii)* a larger fraction of the ejecta will move fast enough to make secondary craters.

Mars. The amount of mass available to make secondaries on Mars is less than that available for either Mercury or the Moon. Table 2 shows that, for the conditions considered here, an impact generates only a little more than a quarter of the mass for secondary cratering on Mars than on the Moon. Nevertheless, every impact on Mars generates at least one impactor mass worth of secondary craters.

Vesta. On the other end of the spectrum is Vesta, which has the smallest resulting secondary population – but note that the value is non-zero. Given that v_{min} is indeed less than v_{esc} on Vesta, secondaries form on that body. The same will be true for any of the large asteroids for which $v_{min} < v_{esc}$.

References: [1] Bierhaus E. B. et al. (2012) *Icarus, in press*. [2] Bart G. D. and Melosh H. J. (2010) *Icarus, 209,* 337-357. [3] Bart G. D. and Melosh H. J. (2010) *JGR*, 115, E8004. [4] Housen K. R. and Holsapple K. A. (2011) *Icarus, 211*, 856-875. [5] Strom R.G. et al. (2011) *LPSC IVII*, Abstract #1079. [6] Chapman et al. (2011) EPSC, 1497.

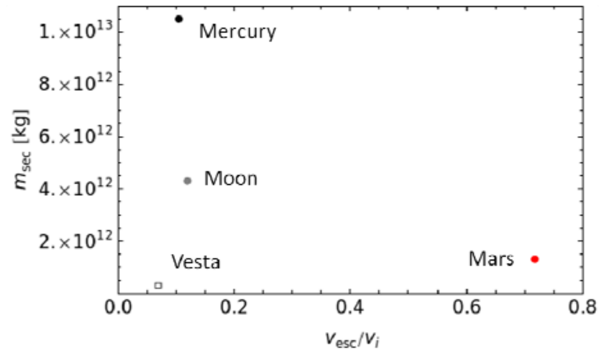

Figure 1. The amount of mass available to make secondaries for a 1 km asteroid impact. Mercury has much more mass available to make secondaries than the Moon and Mars, and may have more secondaries than any other body in the Solar System. This is due to the combination of (1) very high impact speeds, which creates significant amounts of fast moving ejecta, and (2) a large escape speed, which means much of that fast moving ejecta is retained to make secondary craters.

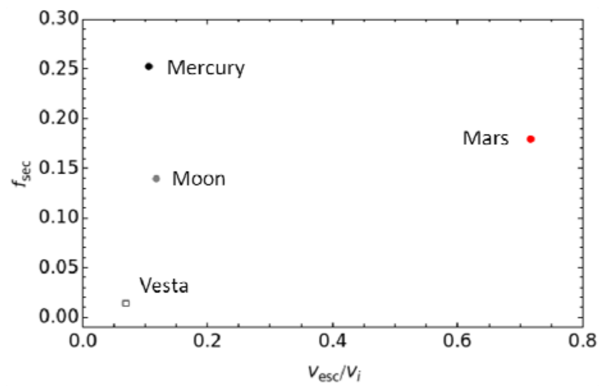

Figure 2. The fractional mass ($f_{sec} = m_{sec}/m_{tot}$) available to make secondaries for a 1 km asteroid impact. Even though Mars is more efficient at holding on to fast moving ejecta, the higher mean impact speed on the Moon creates more fast moving ejecta to make secondaries (Figure 1).

Table 2. D_t, and m_{sec} available to make secondaries in terms of impactor mass for a 1 km asteroid.

Object	D_t [km]	m_{sec}/m_i
Moon	7.7	4.1
Mars	4.7	1.2
Mercury	8.5	10.0
Vesta	6.8	0.3