TRANSFER OF IMPACT EJECTA FROM IO TO EUROPA.

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Introduction: Comet impacts on Io generate numerous high velocity spalls, many of which are ejected at speeds high enough to escape into independent orbits around Jupiter. Many of the spalls ultimately reach Io, and some reach Ganymede. Spalls from Io are the chief source of rocks to Europa's ice shell. The total mass transferred from Io to Europa, the sizes of the rocks, the number of the rocks, and the size, depth, and number of craters that they make, will also be discussed (albeit mostly not in this abstract).

Test particles: We considered four different initial conditions, consistent with launch from four different points on the surface of Io: the apex, the subjovian and antijovian points, and the south pole. We modeled the ejecta velocity distributions using two different models, a scaling (rubble) model from Housen et al. (1983), and a spall model from Melosh (1984, 1985, 1989). The former model describes the lunch of loose rocks or regolith from the surface, while the latter describes the breakup and launch of competent rock. The spall model is more appropriate to Io, where the surface is likely to be at most times and places hard young lavas.

We used Levison and Duncan's Swift numerical integration package to follow the orbital evolution of the ejecta. Swift is a regularized, mixed- variable symplectic (RMVS) integrator that implements the Wisdom and Holman algorithm (1991); for our studies we use the RMVS3 version. It is especially well suited for the interactions of massless test particles with massive bodies. We integrations include the four Galilean satellites, Amalthea and Thebe, Jupiter's higher gravitational moments up to and including J_{12}, Saturn, and the Sun. The integrations and the consistency of the initial conditions were tested against the known behavior of the Laplace resonant argument.

Test particles were integrated for 1000 years. Most particles that escape from Io are ultimately re-accreted by Io. About 8% of the spalled particles are swept up by Europa, about 2% hit Ganymede, and 0.1% hit Callisto. The median time for transfer of ejecta from Io to Europa is 45 years. A small number of particles (0.5%) are still active after 1000 years.

Primary impacts on Io: Jupiter-family comets are the chief source of primary impact craters on the Galilean satellites (Shoemaker and Wolfe 1982). The numbers and sizes of the comets can be inferred from observed craters on Europa (for small comets), Ganymede and Callisto (for mid-size comets), and from the observed size-frequency distribution of Kuiper Belt Objects (for big comets). To relate comet size to crater size we assume that comets have a density of 0.6 g/cm^3 and impact velocities given in Zahnle et al. (2003). The impact rate is most directly determined from the historical record of observed close cometary encounters with Jupiter. The rate that comets strike Io can be described by a cumulative size distribution assembled from four power laws (Zahnle et al 2003). This distribution is markedly deficient in both large (>30 km diameter) and small <1 km diameter) bodies compared to asteroids. The cumulative distribution is apt for use as a generating function for Monte Carlo modeling.

Amount of material transferred: Theory suggests that the larger spalls are regular black rectangular parallelpipids of dimension 1:4:9 (Clark, 2001, 2010). However, like spinning plates they are prone to break, so we presume that what hits Io are equant objects with dimensions comparable to the smallest dimension of the primary spall plate. Uisng Melosh's theory we find that, for comet impacts in basalt, the larger spalls are roughly 0.3% the size of comet (so that e.g. a 1 km diameter comet generates 3 meter blocks of basalts).

Recent investigations of the Zunil crater on Mars (McEwen et al 2005) provides ground truth. Zunil is a very young 10.1 km diameter impact crater set in a young volcanic province. Its secondaries are numerous and distinctive. McEwen et al estimate that there are 10^7 secondaries bigger than 10 m diameter within 800 km of the primary. With the help of sophisticated 3D hydrodynamical numerical simulations, McEwen et al infer that the observed secondary craters imply that there are globally on Mars 10^8 Zunil secondaries bigger than 10 m. Most of these more distant secondaries are made by ejecta launched fast enough to escape Io.

Because it is set in young volcanic country, Zunil is an excellent analog to craters on Io. Hard rock gravity scaling suggests that the analogous crater on Io would be $10.1 \text{ X } (375/180)^{0.22} = 11.8$ km diameter. The explosion that makes an 11.8 km crater on Io would have the same velocity field as the explosion that makes a 10.1 km crater on Mars (apart from near field effects that). McEwen et al's numerical models predict that $1.2\text{x}10^{15}$ g of ejecta were launched faster than 2.6 km/s, Io's escape velocity. An 11.8 km crater on Io is made by a $6\text{x}10^{14}$ g comet. Hence we conclude that the typical comet striking Io ejects twice its mass into orbit about Jupiter, 8% of which eventually hits Europa.

To better understand the statistics of these events, we have performed a series of Monte Carlo simulations. Each simulation is run for the duration of a time window. The four time windows we used were 100, 10, 1, and 0.1 Million years. To obtain clean differential distributions we ran four million trials for each of the four time windows.

Figures 1 and 2 provide different perspectives on the statistical properties of these events. In Figure 1 we look at the cumulative distributions for the four time windows on a standard probability plot. Figure 1 directly shows the probability that more than (or less than) a certain amount of mass is transferred to Europa during a given time interval. Robust statistical measures like the median and the quartiles are evident at a glance. Figure 1 shows one thing that is obvious and another that is less so. The obvious thing is that, in general, less material is transferred in shorter time windows. Less obvious is that, in the median, markedly less material is transferred in the shorter time windows. This occurs because small comets are rare.

The shapes of the distributions are better seen when plotted in differential form (Figure 2). Figure 2 is a histogram. The (differential) probability is binned according to the amount of mass transferred. The width of an individual bin is $10^{0.1}$ times the total mass transferred from Io to Europa in a given trial. A factor of $10^{0.1}$ is by definition a decibel. The total probability is normalized to unity. The mean, median and the quartiles are indicated, the former by boxes and the latter by crosses.

Figure 2 shows that the longer time intervals give tighter distributions and have better defined means than do the shorter time intervals. This arises from the monotonically steepening slope of the comet size-frequency distribution. As the distribution steepens the dispersion between comet masses narrows and the distribution tightens. The shorter time intervals, especially the 0.1 Myr window, give extremely broad distributions.

As an example consider the 1.0 Myr time window. In any million year interval the amount of material transferred to Europa is usually modest. The median is 3x10^{14} g. Half the trials give between 6x10^{13} and 1.5x10^{15} g. Thus, in a typical million year time window, basalt is shipped to Europa at a rate of 2-50 g/s. The median rate is 10 g/s. This is somewhat smaller than the estimated 45 g/s micrometeoroid flux (Cooper et al 2001, Johnson et al 2001). By contrast the mean is 10^{16} g (300 g/s) is distinctly bigger than the micrometeoroid flux.

On longer time scales the amount of basalt transferred from Io to Europa exceeds the micrometeoroid flux. The median and mean over any 10 Myr window are 70 g/s and 450 g/s, respectively. Over 100 Myr the median and mean rise to 200 g/s and 600 g/s, respectively. In other words, most of the rocks and stones currently in or on Europa's ~60 Ma ice shell are impact ejecta from Io.

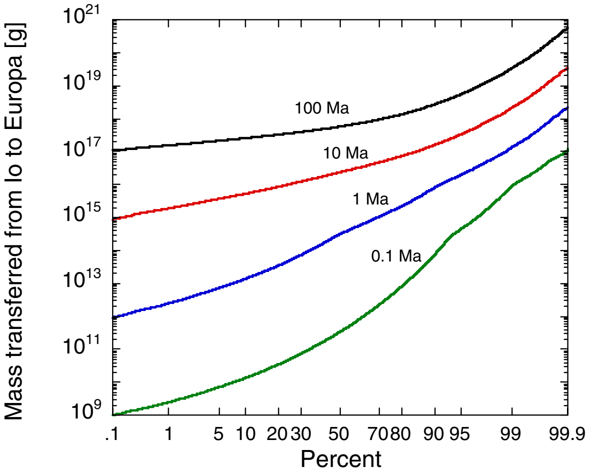

Figure 1. Probability plot of mass transferred from Io to Europa as ejected rocks over four different time windows.

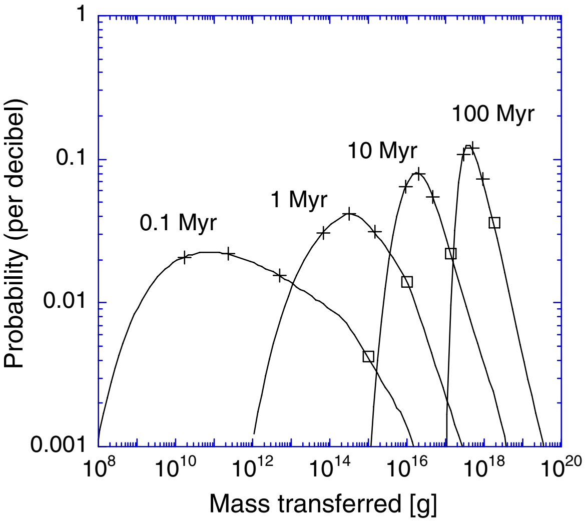

Figure 2. Differential distributions (histograms) of mass transferred from Io to Europa as ejected rocks over four different time windows. Quartiles, medians, and means (open boxes) are indicated.