Advances in dynamic fracture with applications to planetary cratering. Olivier S. Barnouin-Jha,[1] Kaliat T. Ramesh [2], P.K. Swaminathan[1] [1]Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723 (olivier.barnouin-jha@jhuapl.edu; pk.swaminathan@jhuapl.edu); [2]Dept. of Mechanical Enginerring, Johns Hopkins University, Baltimore, MD 21218 (ramesh@jhu.edu).

Introduction: Radial and concentric faults, and lineaments and grooves have all been identified in associations with impact craters on the planets and asteroids [e.g., 1, 2]. These, along with ejecta size-distributions are in most instances the direct result of dynamic fracture during impact cratering. Such dynamic fracture is well studied both in the laboratory and in the field in two strain rate regimes. The first is typically encountered during small scale high-velocity impact experiments. Strain rates encountered in such experiments are on the order of 10^5 to 10^6 s^{-1} and lead to massive fragmentation. The second regime is found during earthquakes, where fracturing takes place under loading that corresponds to nominal strain rates of 10^{-2} to 10^{-3} s^{-1}, with a relatively small number of very large cracks. The strain rates encountered during impact cratering (i.e., when an asteroid slams into a planet) are very different, ranging from 1 to 100 s^{-1}. Classic Grady-Kipp dynamic fracture models [3] work well at high strain rates, but they do not apply for these intermediate strain rates. Indeed, these often over predict the grain-size distribution of ejecta at planetary craters. We have begun laboratory experiments and numerical studies to explore this intermediate regime taking into account new advances in impact fracture physics.

Recent advances in impact fracture physics: Past classic models in impact fragmentation [e.g., 3] have relied on energetics: that is, they assume that all of the kinetic energy associated with the impact is converted into fracture energy, resulting in a fragment population. Recent work [4] has demonstrated that it is critical to also account for the dynamics: that is, there is a significant residual kinetic-energy associated with the propagation of waves within the fragments, as well as a significant probability of further fragmentation as a result of inter-fragment collisions. This results in fragment sizes and fragment size distributions [5,6] that are significantly different from classical predictions. A key result of our improved understanding of the physics of impact fragmentation is that there is a very strong effect of the strain rate on the fragmentation process. In particular, it has been demonstrated that the fractures and fragment sizes that are developed at intermediate strain rates are dramatically different (by more than an order of magnitude) than those predicted by classical models.

This is a critical result, because the bulk of the impacted body sees relatively low strain rates, even for a hypervelocity impact. As an example, the overall strain rate range in the bulk of a 10 meter diameter body subjected to an impact at 10 km/s is 10^3 s^{-1}, even though local strain rates at the location of the impact will be well over 10^6 s^{-1}. For a rocky body, the normalized strain rate corresponding to this would be 10^{-1} – 10^0, and Figure 1 shows that the deviation from the classical Grady-Kipp model (the straight line in the Figure) is well over an order of magnitude.

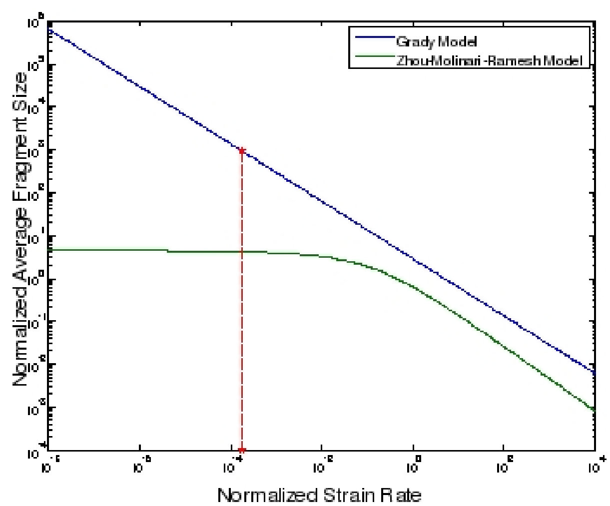

Figure 1: Fragmentation after impact. The green line is the new model developed at Hopkins, while the blue line is the old standard (Grady-Kipp). The red line indicates the normalized strain rate corresponding to a planetary impact for basalt (a good model material for Martian surface, for example). Note the big difference in predicted fragment sizes.

A second major advance that has occurred over the last decade is in our understanding of the effects of defects on the fracture process. Cracks in brittle materials most likely nucleate from pre-existing defects, or flaws. Since the probability of finding a critical flaw increases with the size of the brittle solid, it follows that there should be a significant size effect on the fracture of brittle materials. This has been observed in great detail in rocks [7]. However, until recently, the interaction of the pre-existing defect distributions with the rate of loading was not understood. Recent laboratory studies using non-geologic ceramics show that at low rates of loading the largest pre-existing defect dominate the failure process; however, at intermediate and higher rates of loading the majority of the defect distribution participates in the fracture process. This has strong implications for the scaling of impact fracture processes.

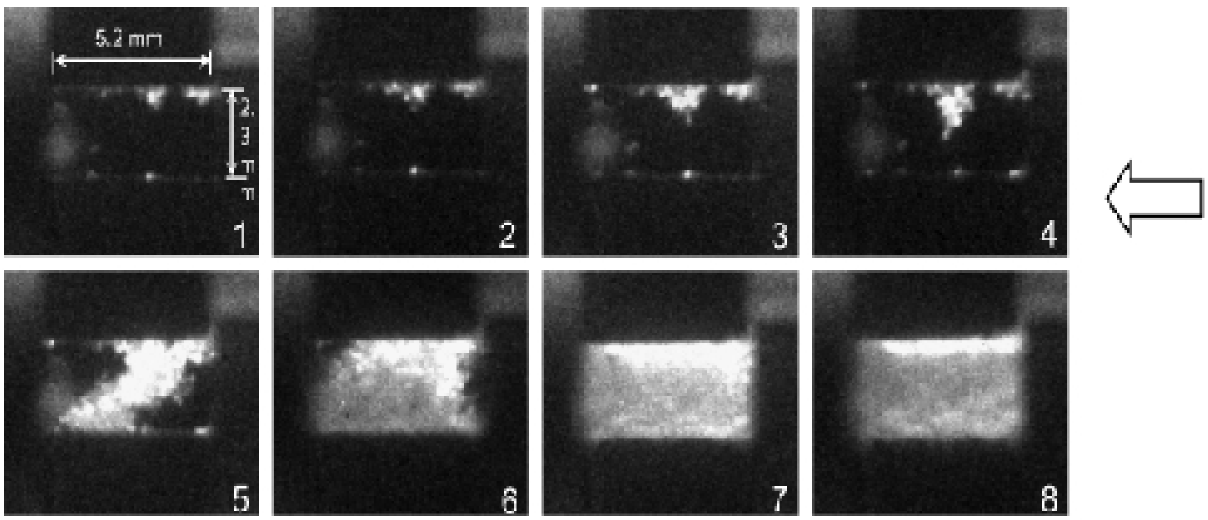

Figure 2: High-speed photographs showing the failure process using a transparent polycrystalline ceramic. The bright spots are new cracks. The nominal strain rate of this experiment is 10^3 s^{-1}. This is the strain rate that occupies the bulk of the volume during impact on a large body, as in planetary impact by an asteroid.

Experiments and applications to planetary cratering: Figure 2 illustrates the type of experiment performed. A translucent quartz target will be used to visualize propagation of fractures within the target. Experiments will be conducted over a range of impact velocities and specimen sizes to obtain a range of strain rates and a measure of size effects. In each case, real-time experimental diagnostics include projectile velocity and tilt, local stress state using PVDF gauges at the sample-block interface and the high-speed photography. Post-mortem analysis include fragment size distribution and fracture surface characterization, as well as analysis of fragments through scanning electron microscopy.

Use of the current and future empirically derived constitutive and fracture models obtained from our ceramic and quartz target are then used to estimate fragment sizes generated by craters formed on planets and asteroids. In the preliminary work shown here, we use strain rate estimates derived from the CTH hydrocode calculations for impacts into both homogeneous and heterogeneous planetary targets to calculate fragment-size distribution from an analytical version of the empirical fracture model. At a later times, we will directly introduce a numerical version of the model within CTH. We eventual expect to produce a new fracture scaling rule.

Preliminary results from Figure 1 clearly indicate that a greater number of fines are generated than predicted by [3], which is more in line with the vast amounts of fines observed at lunar craters [8]. The average size of large blocks is also likely to be smaller, which may have important implications for how many secondaries individual craters can form, thereby influencing the current debate on the production of small craters on planetary surfaces [e.g., 9].

References: [1] Melosh, H.J., *Impact Cratering: A Geologic Process*, Oxford Univ. Press, 1989. [2] Asphaug E. and H. J. Melosh (1993), *Icarus 101*, 144-164. [3] Grady D.E. and Kipp M.E., *Mechanics of Materials, 4*, 311-320, 1985. [4] Zhou, F.H., J.F. Molinari, and K.T. Ramesh, *International Journal Of Solids And Structures,*42(18-19), 5181-5207, 2005. [5] Zhou, F., J.F. Molinari, and K.T. Ramesh, Applied Physics Letters, 88(26), 2006. [6] Zhou, F.H., J.F. Molinari, and K.T. Ramesh, I*nternational Journal Of Fracture, 139(2*), 169-196, 2006. [7] Housen, K.R. and K.A. Holsapple (1999), *Icarus, 142(1),* 21-33, 1999. [8] Schultz, P.H. and W. Mendell *PLPSC IX*, 2857-2883, 1978. [9] McEwen et al., *Icarus 176*, 351- 381, 2005.