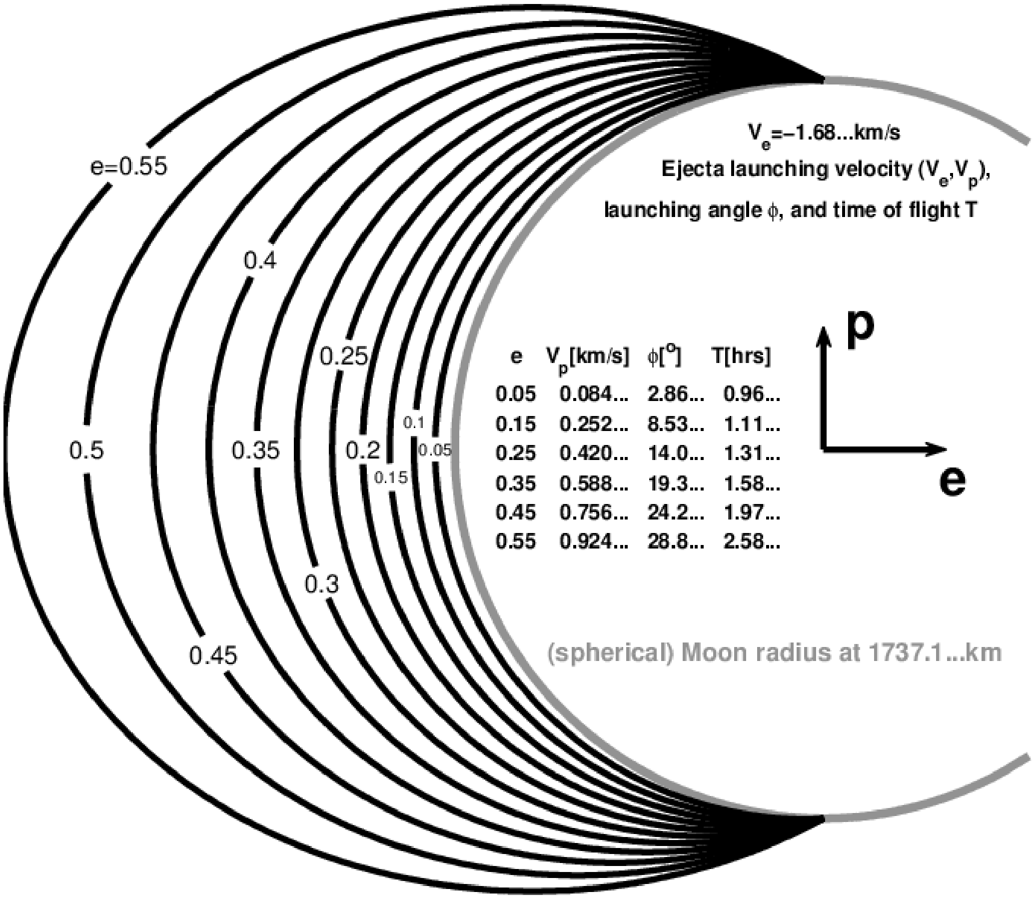
A BALLISTIC MODEL FOR ANTIPODAL IMPACT MELT DEPOSITS ON THE MOON.

Per Jögi and David A. Paige[1] [1]Department of Earth, Planetary and Space Sciences, UCLA, Los Angeles, CA 90095, jogi@physics.ucla.edu

Introduction: LRO LROC high resolution images, Diviner rock abundance maps, and MiniRF backscatter images have revealed the presence of hundreds of anomalous blocky young melt deposits in 150 km diameter region that includes the antipode of Tycho Crater on the far side highlands [1, 2]. The deposits are on the order of 5 meters think, and show many of the same characteristics of impact melts, including distinct evidence for flow and ponding. While the apparent age of these deposits is consistent with that of the Tycho impact, the concept of focusing of impact ejecta at the antipode is plausible, the clear appearance of low-viscosity melt-related morphologies in these features has proven difficult to explain. Artemieva [3] has employed a 3D hydrocode model to simulate the ejection of solid and molten material from the Tycho impact and the ballistic trajectories of a subset of this material to the antipode. Since impact velocities at the antipode of on the order of 2 km/sec are not sufficient to result in remelting, Artemieva suggests that partially molten impact bombs with diameters of greater than 1 meter are the source of the observed melt features. However, impact ejecta are known to follow a power law size distribution, with a substantial fraction of the ejected mass contained in small particles [4]. Furthermore, the absence of obvious re-impact features and the low viscosity morphologies of Tycho antipodal melts seems difficult to reconcile with the molten impact bomb hypothesis. Here we propose an alternative explanation for these features that involves frictional heating from accumulating ballistically emplaced ejecta.



e	V_p[km/s]	ϕ[°]	T[hrs]
0.05	0.084...	2.86...	0.96...
0.15	0.252...	8.53...	1.11...
0.25	0.420...	14.0...	1.31...
0.35	0.588...	19.3...	1.58...
0.45	0.756...	24.2...	1.97...
0.55	0.924...	28.8...	2.58...

Fig. 1. Antipodal ejecta trajectories for 2-body dynamics for eccentricities $0.05<e<0.55$. Initial and final horizontal and vertical velocities (Ve and Vp), launching angle ϕ and time of flight *T* are also shown.

Ballistic Model: The ejecta debris flight path is assumed to be equal to the trajectory of the secondary particle executing a simple 2-body dynamics. An exterior trajectory reconnection of two antipodal sites on a spherical boundary surface of radius r_M admits only ellipse shaped paths. Given a coordinate system fixed at the center of the primary (the Moon with mass $m_M = 73.42 \times 10^{21}$kg) with axes in unit vector directions $\hat{\boldsymbol{e}}$, $\hat{\boldsymbol{p}}$, and $\hat{\boldsymbol{h}}$, then the trajectory of the secondary (ejecta debris), r, is known through the true anomaly, θ (measured from $\hat{\boldsymbol{e}}$ in the $\hat{\boldsymbol{e}}$, $\hat{\boldsymbol{p}}$ plane; polar coordinates), $r = \frac{r_M}{1+e\ \cos\theta}$ where e $(0 \le e < 1)$ is the eccentricity of trajectory and $a = \frac{r_M}{1-e^2}$ is its semimajor axis. In this perifocal frame the position,$\boldsymbol{r}$, and the ty,$\boldsymbol{V}$, vectors of the secondary are $\boldsymbol{r} = r(\hat{\boldsymbol{e}}\cos\theta + \hat{\boldsymbol{p}}\sin\theta)$ and $\boldsymbol{V} = \sqrt{\frac{\mu_M}{r_M}}(-\hat{\boldsymbol{e}}\sin\theta + \hat{\boldsymbol{p}}(e + \cos\theta))$where $\mu_M = Gm_M$ with G the universal gravitational constant. At the ejecta site $\theta = {}^{\pi}/_{2}, r = r_M$ and the initial velocity is $\boldsymbol{V}_{\pi/2} = \sqrt{\frac{\mu_M}{r_M}}(-\hat{\boldsymbol{e}} + \hat{\boldsymbol{p}}\ e) \equiv (V_e, V_p)$ and at its antipodal, recollision, site $\theta = 3\,{}^{\pi}/_{2}, r = r_M$ such that $\boldsymbol{V}_{3\pi/2} = \sqrt{\frac{\mu_M}{r_M}}(\hat{\boldsymbol{e}} + \hat{\boldsymbol{p}}\ e) \equiv (-V_e, V_p)$. The launching angle, ϕ, is $\phi = \tan^{-1}\frac{V_p}{|V_e|} = \tan^{-1} e$ and the time of flight is function of e as $T(e) = 2\sqrt{\frac{{r_M}^3}{\mu_M(1-e^2)^3}}(\pi - 2\tan^{-1}\sqrt{\frac{1-e}{1+e}} + e\sqrt{1-e^2}\,)$. Fig 1 gives sample trajectories and tabulates some of their flight parameters.

Frictional Heating Model: While the ponded Tycho antipodal melt deposits we observe today are on the order of 5 meters thick, they derive from a thinner and much more widely distributed accumulation of ejecta that may have had an effective thickness on the order of one meter or less. We propose that the antipodal ejecta consisted largely of smaller particles that had ample time to solidify during their ~2 hour trajectory from the initial impact site. However, the results of the ballistic model show that there is a ~2 hour range of possible travel times from the initial impact site to the antipode. These travel-time differences would result in a rather intense and prolonged bombardment of ejecta particles at the antipode. We estimate that the frictional heating of the impacting ejecta during this bombardment period should produce sufficient frictional heat to result in remelting of the accumulating ejects.

In rough terms, if one half meter of antipodal ejecta with a density of 3000 kg/m3 and with an impact velocity of 2 km/sec were to accumulate over a timescale of 2 hours, this would result in the deposition of 6×10^9 Joules/m^2. If this amount of energy per square meter were radiated by a blackbody to space during this period, it would achieve surface temperature of greater than 1640K, which is higher than the silicate liquidus temperatures of ~1450K. Alternatively, assuming a specific heat capacity of 800 Joules/kg, the deposited energy would be sufficient to raise the temperature of the ejecta by 2500K. The results of this order of magnitude calculation suggests that frictional heating of antipodal ejecta imparts more than enough energy to melt the accumulating deposits, and thus explain their apparent low viscosity.

References: [1] Robinson, M. S. et al. (2011) *LPSC*, 42, 2511. [2] Bandfield, J. L. et al. (2013) *LPSC* 44, 1770. [3] Artemieva, N. (2013) *LPSC* 44, 1413. [4] O'Keefe, J. D. and Ahrens, T. J. (1985) *Icarus* 62, 328-338.