AN IMPACT EROSION STABILITY LIMIT CONTROLLING THE EXISTENCE OF ATMOSPHERES ON EXOPLANETS AND SOLAR SYSTEM BODIES. D. C. Catling[1] and K. J. Zahnle[2], [1]Dept. Earth and Space Sciences/ Astrobiology Program, Box 351310, University of Washington, Seattle WA 98195, USA (dcatling@uw.edu), [2]MS 245-3, Space Science Division, NASA Ames Research Center, Moffett Field, CA 94035, USA.

Introduction: In the Solar System, some odd couples provide clues about what controls the presence or absence of atmospheres. For example, Ganymede and Titan are comparable in size and mass but Ganymede is essentially bereft of an atmosphere while Titan's atmosphere is thick. Clearly, the escape velocity on its own does not determine whether an atmosphere exists. Instead, a physically plausible explanation is that Ganymede sits in the large gravity well of Jupiter and so has been subject to energetic impacts that would have removed any atmosphere by impact erosion [1]. (See [2] for a general discussion of atmospheric escape). In contrast, Titan's atmosphere has survived and accreted in the smaller gravity well of Saturn. Thus, whether atmospheres exist or not depends upon exposure to energetic impacts that remove more volatiles than delivered. Here we propose that this phenomenon is more general than widely appreciated and applies across exoplanetary systems as well as the Solar System.

Data suggest the importance of impact erosion: To determine whether impact erosion is a plausible factor controlling whether atmospheres exist, we examined data for the Solar System and beyond. Fig. 1 plots the median impact velocity v_{impact} (related to the specific energy (J/kg) needed for erosion), versus the escape velocity v_{escape}, for various bodies (related to the specific energy required for volatiles to escape). The plot includes planets and minor bodies of the Solar System and transiting exoplanets. In the Solar System, we identify a dividing line of $v_{impact}/v_{escape} \approx$ 5-6 that separates those bodies that have atmospheres from those that do not. We can think of this line as a limit beyond which "anti-accretion" occurs where there is net erosion of volatiles. Amongst exoplanets, we find some bodies that lie on the upper left side of the line in the "no atmosphere" zone. These bodies (plotted in orange) include Corot 7b, Kepler 10b, Kepler 9d and Kepler 21b. Plotted in pink are KOI 55b and KOI 55c, which orbit the leftover core of a red giant.

Theory: An obvious question is why a stability limit should occur at $v_{impact}/v_{escape} \sim$ 5-6. Early lab experiments concerned with silicate-on-silicate impacts suggested that anti-accretion occurs at $v_{impact}/v_{escape} \sim 8$ [3]. In contrast, the "tangent plane" model [4], which is concerned with atmospheric erosion, has a threshold at $v_{impact}/v_{escape} > 2$ where atmospheres are eroded. However, the factor of ~2 is only a rough approximation [4]. On this basis, we might expect a threshold to lie within $v_{impact}/v_{escape} \approx$ 2-8.

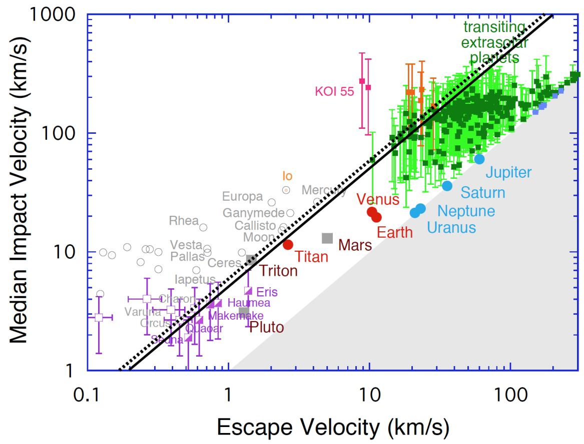

Fig. 1. An empirical impact erosion stability limit for atmospheres, $v_{impact}/v_{escape} = 5$ (solid line), $v_{impact}/v_{escape} = 6$ (dotted line). The shaded zone in the lower right is an unphysical region, because an impactor has to have a velocity that is minimally the escape velocity from energy conservation. Solar System bodies with atmospheres, such as Earth, are plotted in solid colors. Bodies in the Solar System that are devoid of atmospheres are plotted with open gray symbols. Kuiper Belt Objects are purple. Transiting exoplanets that conform to the stability limit are plotted in green. Exoplanets that lie off the stability limit are plotted in orange or pink.

Tangent plane model. In the tangent plane model, the Hugoniot equations (of shock fronts) and energy conservation imply that the impact velocity needed for the impact plume to reach escape velocity is related to the escape velocity as follows, for like-on-like materials such as asteroids hitting rocky bodies or comets hitting icy bodies:

$$v_{impact} = \frac{2}{\sqrt{h}}(v_{escape}^2 + 2L_{vap})^{1/2}$$

Here, L_{vap} is the latent heat of vaporization of impactor and target and h is a heating efficiency factor (< 1). Similar equations exist for unlike materials such as comets hitting rocky bodies. For large escape velocities, $v_{impact}/v_{escape} \approx 2/\sqrt{h}$. Taking h to be 10-20%, it follows that $v_{impact}/v_{escape} \approx 4.5\text{-}6$ for erosion. However, in detail, an integral needs to be taken over all impact velocities in a population of impactors.

There are a couple of problems with the tangent plane approximation. One is that erosion versus accretion is a "step function". A second snag is the need to specify uncertain factors such as heating efficiency, h. Numerical models get around these problems.

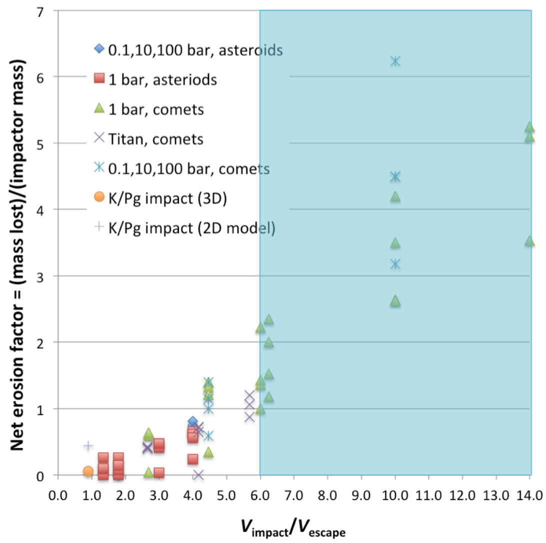

Fig. 2. Compilation of hydrocode results for impacts on Earth, Mars and Titan-sized bodies. Blue shading indicates net erosion. The surface atmospheric pressure and impactor type are listed. K/Pg = Cretaceous/Paleogene impact.

Numerical models. In hydrocodes, the ratio of the total mass that escapes, m_{escape}, to the mass of impactor, m_{impactor}, can be calculated. This ratio, $m_{\text{escape}}/m_{\text{impactor}}$, is a net erosion factor that exceeds unity when there is no accretion of atmospheric volatiles.

Fig. 2 shows a compilation of various hydrocode results [5-7]. Dispersion occurs because of different assumed impactor and target materials as well as a weak dependence on the impactor mass. However, overall 3D hydrocodes show that $m_{\text{escape}}/m_{\text{impactor}}$ exceeds unity when $v_{impact}/v_{escape} \approx 4.5\text{-}6$. All models show erosion at $v_{impact}/v_{escape} > 6$, consistent with Fig. 1.

Applications. Giant planets near their host stars might have lost their atmospheres because of hydrodynamic thermal escape [8], leaving behind rocky cores. However, some models cannot fully remove atmospheres from Jupiter-mass planets [9] or proposed former hot Neptunes [10]. Because exoplanets in tight orbits will also be subject to impact erosion, this mechanism should also be considered.

Probable densities of 5-9 g/cm^3 suggest that Corot 7b, Kepler 10b, Kepler 9d and Kepler 21b are rocky while Fig. 1 implies that they are devoid of atmospheres. Ref. [10] argues that the rate of thermal escape is too small for CoRoT-7b to have once been an ice giant, and likewise for 4.6±1.2 $M_{\oplus}$ Kepler-10b despite its 0.017 AU orbit of a G star. However, impact erosion provides an alternative means of atmospheric loss.

Impact erosion or thermally-driven hydrodynamic escape? In hydrodynamic escape, the stellar flux, F, depends on orbital distance r_{orb} as $1/r_{\text{orb}}^2$. Since the square of the orbital velocity v_{orb}^2 varies as $1/r_{\text{orb}}$, then $F \sim v_{\text{orb}}^4$. Roughly, $v_{impact} \sim v_{orb}$, so the thermal escape limit has the same functional form as impact erosion, i.e., $F \sim v_{\text{impact}}^4 \sim v_{\text{esc}}^4$. This creates degeneracy in trying to decide whether impact erosion or thermal evaporation leads to atmospheric loss (Fig. 1).

However, some features might distinguish whether thermal escape or impact erosion has been responsible for atmospheric loss. In the Solar System, the Galilean satellites are firmly on the "no atmosphere" side of the impact boundary but they are borderline for a thermal evaporation limit [8]. For exoplanets, the two limits will be parallel but offset for different spectral types of stars if extreme ultraviolet (EUV) is an important factor for thermal escape. Lastly, hydrodynamic escape produces mass fractionation of isotopes [11] whereas impact erosion does not, although whether this will ever be detectable for exoplanets is unclear.

Conclusions: ***We hypothesize that planets with atmospheres (including those that are habitable) will only occupy a region where*** $1 \leq v_{impact}/v_{escape} \leq 5\text{-}6$. The upper limit is consistent with hydrocode model results. We predict no planets with atmospheres where the threshold is exceeded, which is testable. Specifically, for $v_{impact}/v_{escape} > 6$, we predict no low density Super-Earths with significant volume of H_2-He envelopes, no Neptunes, no Earths, no Venuses, and no Titans. Instead, we predict only lifeless and barren bodies, such as Super-Mercurys, Super-Ios or airless icy bodies. Exoplanet parameters support our hypothesis because the $v_{impact}/v_{escape} > 6$ zone is devoid of low density Super-Earths and only contains dense bodies.

We emphasize that impact erosion is a firm boundary on the presence or absence of atmospheres. To address the question of whether atmospheric loss by thermal escape is also important, we suggest examining (in the future) a dependence of the presence of an exoplanet atmosphere on the EUV flux of the host star.

References: [1] Zahnle K. et al. (1992) *Icarus* 95, 1.
[2] Catling D. C., Zahnle K. L. (2009) *Sci. Am.* 300, 36.
[3] O'Keefe J. D., Ahrens T. J. (1977) *Science* 198, 1249.
[4] Melosh H. J., Vickery A. M. (1989) *Nature* 338, 487.
[5] Shuvalov V. (2009) *Meteorit. Planet. Sci.* 44, 1095.
[6] Korycansky D. G., Zahnle K. J. (2011) *Icarus* 211, 707.
[7] Hamano K., Abe Y. (2010) *Earth Planets Space* 62, 599.
[8] Zahnle K. J., Catling D. C. (2013) *44th Lunar Planet. Sci. Conf.*, this conf.
[9] Murray-Clay R. A. et al. (2009) *Astrophys. J.* 693, 23.
[10] Leitzinger M. et al. (2011) *Planet. Space Sci.* 59, 1472.
[11] Hunten D. M. et al. (1987) *Icarus* 69, 532.