TIDALLY-DRIVEN SEISMICITY ON SATELLITES, PLANETS AND EXOPLANETS. T.A. Hurford[1], W.G. Henning[2], R. Maguire[2,3], V. Lekic[2], N. Schmerr[2], M. P. Panning[4], V.J. Bray[5], M. Manga[6], S.A. Kattenhorn[7], L.C. Quick[1], and A.R. Rhoden[8], [1]NASA Goddard Space Flight Center, Greenbelt, MD 20771 (Terry. A. Hurford@nasa.gov), [2]University of Maryland, College Park, MD 20742, [3]University of New Mexico, Albuquerque, NM, 87131, [4]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, [5]University of Arizona, Tucson Az, 85721, [6]University of California, Berkeley, Berkeley, CA 94720, [7]University of Alaska Anchorage, Anchorage, AK 99508, [8]SouthWest Research Institute, Boulder, CO 80302.

Introduction: The seismic activity of tidally-driven planets and moons outside the Earth-Moon system is unknown, and even the tidally-driven activity of Earth's Moon remains poorly constrained. Notwithstanding, we do know that: 1.) the Moon's seismic activity is driven by tidal interactions with the Earth; 2.) tidal control of activity from fractures has been observed on Enceladus [1,2]; and, 3.) complex tectonic fabrics are observed on many tidally-influenced bodies in our Solar System.

We outline an approach for estimating the size and frequency distribution of seismic events on tidally active worlds. In doing so, we quantify how tides may affect the timing and location of events occurring on these bodies. In developing this framework, we use the Moon to constrain links between tidal dissipation and seismic activity, survey seismic activity on different tidally-active worlds, and apply the model to Europa [3].

Tidal dissipation and seismic energy: The total amount of energy dissipated within a spin-synchronous body due to reworking from orbital eccentricity over a time period, t, can be defined as

$$E_T = \left(\frac{k_2}{Q}\right)\left(\frac{21}{2}\, e^2\right)\left(\frac{G\, M_p^2\, n\, R^5}{a^6}\right) t \qquad (1)$$

where k_2 is the second order gravitational Love number of the body's response to the tide-raising potential, Q is the quality factor describing the dissipation of energy per cycle within the body, e is the orbital eccentricity, M_p is the mass of the tide-raiser, n is the mean motion of the body, R is the body's radius, and a is its orbital semi-major axis. Typically, this equation is presented in the form of an orbit average of tidal power (in Watts); here, we instead choose to account for the total tidal energy E_T (in Joules) dissipated in an arbitrary time period, t. Because the derivation of Eq. 1 assumes an average tidal dissipation per orbit, it is best to select t to be an integer number of orbital periods. Equation (1) describes all of the energy lost to the interior of a body from eccentricity tides and in planetary applications it has been assumed that *all* of this energy is dissipated as heat within the interior. In reality, (1) represents the sum total of energy available for tidally driven processes, among which viscous heating is probably dominant.

Creation of an event catalog: Following work by Golombek et al. [4] for Mars and extended to Europa by Panning et al. [5], we can define likely activity levels using an assumed Gutenberg-Richter relationship, usually written as

$$\log_{10} N(M_W) = a - bM_W,$$

but rewritten as in Golombek et al. [4] as

$$N(M_0) = AM_0^{-B},$$

where $\log_{10} M_0 = 1.5M_W + 9.1$, $a = \log_{10} A - 9.1B$, b < 1.5 and $b = 1.5B$. The cumulative moment release is

$$\Sigma M_0 = \frac{AB}{1-B}(M_0^\star)^{1-B},$$

where $M_0^\star$ limits the size of the largest event. Thus, seismic event statistics can be defined with 3 parameters (b, ΣM_o and $M_0^\star$).

Constraints from the Earth-Moon System: Based on the cataloging of Lunar seismic events, the b parameter for Lunar seismicity is not well constrained. High frequency teleseismic events in the shallow subsurface of the Moon follow a distribution with a low value, $b \sim 0.5$, while other studies have concluded that b can be as high as 1.78 [6,7]. With the range of b values so broad, most studies adopt a b value of 1.0. Based on the seismic record detailed in Oberst [8] and the result from Nakamura [6], we adopt a b value of 1.0 for our Lunar constraint analysis.

While studies tend to look at Lunar data on yearly periods, this timescale is somewhat arbitrary. Based on the frequency of the largest shallow seismic events, we find that seismic moment seems to build up and be released over roughly 10 orbital cycles. For the Moon, over a period of 10 full tidal cycles, the total energy dissipated is ~ $5\text{x}10^{16}$ J. During a 10 orbital cycle period, the average of the total moment release, ΣM_o, is ~ $8\text{x}10^{14}$ Nm. This represents a conversion factor between energy dissipation and total moment release of ~ 0.017. Using a tabulation of events provided in Oberst [8], we find that a value of $M_0^\star$=$2.5\text{x}10^{14}$ Nm (M_W 3.5) is needed to predict the correct number of seismic events (Fig. 1). Moreover, the largest seismic events represent about 70% of the total moment released.

Tidal dissipation and seismic activity:

Assuming that the constraints on our model placed by Lunar seismic activity are representative of tidally-driven seismic activity, we can explore the seismicity of a variety of tidally-active worlds. Estimating the amount of energy tidally dissipated in these worlds allows us to predict the amount of total seismic moment released over 10 orbital cycles; the largest events predicted would represent 70% of the total moment released. We have explored the seismicity of satellites in our Solar System, other terrestrial planets and activity on exoplanets.

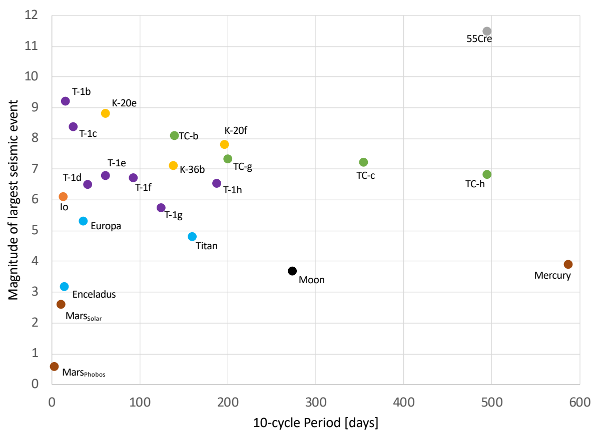

Figure 1: In a survey of tidally-active worlds the largest events predicted in a 10-orbiral period cycle are defined based on an estimate of total energy dissipated. Known exoplanets (T=TRAPPIST, TC= Tau Ceti, K=Kepler) should experience high amounts of tidal dissipation and would likely exhibit frequent, large seismic events. Many satellites in the outer Solar System are as seismically active as the Moon. Tidal processes should also drive seismic activity on terrestrial planets.

Looking more closely at various tidally-active bodies, we can explore the consequences of temporal and spatial variations in tidal dissipation. The tidal dissipation rate over an orbit oscillates by 14% and this would lead to temporal variation in seismic activity. Moreover, spatial rate of tidal dissipation within a body, as shown with the Europan example, is not uniform. This heterogeneity can also affect the location of seismic events (Fig. 2).

Conclusions and Discussion: Tidally-driven dissipation should drive seismicity in bodies that experience tidal processes. Observations of this seismic activity can help explore the interiors of planets and satellites in our Solar System. This work also predicts the seismic events on Titan [10], which might be observed by the Dragonfly New Frontiers mission.

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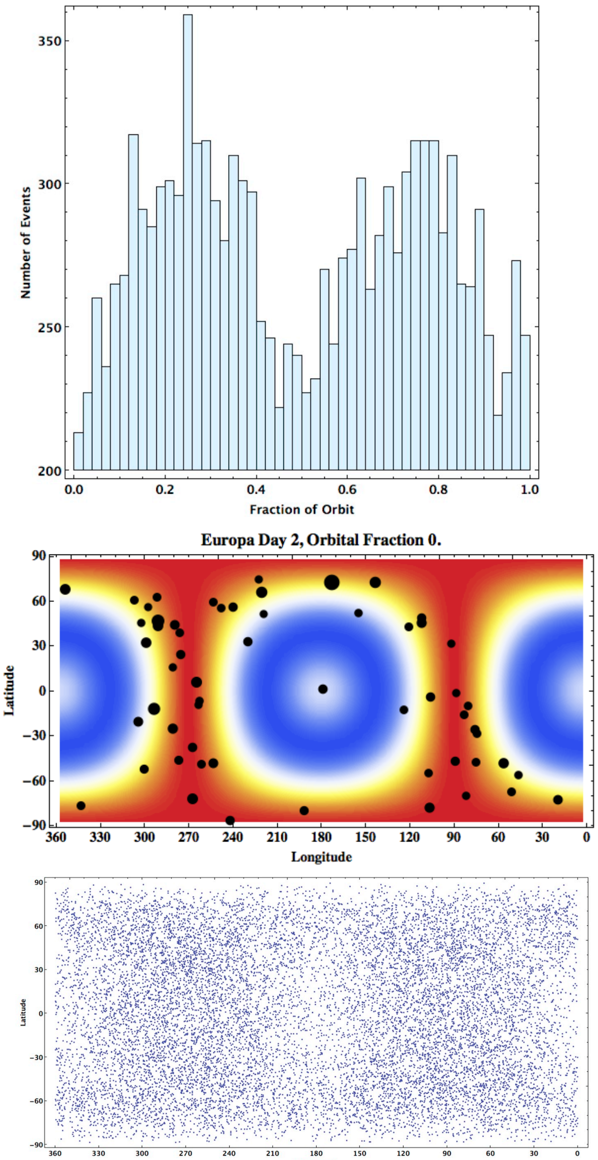

Figure 2: (Top) A histogram of predicted seismic activity on Europa that reflects the variations in tidal dissipation rate throughout an orbital cycle. (Middle) Seismic events predicted near pericenter of Europa's orbit are shown; contours show the spatial distribution of the rate of tidal dissipation with warmer colors representing more tidal dissipation. The sizes of the circles are proportional to magnitude. (Bottom) Over a 10-orbit cycle the combined changes in dissipation rate predict fewer seismic events in the sub/anti Jupiter regions of Europa.