TIDALLY-DRIVEN SEISMICITY: AN APPLICATION TO EUROPA.

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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.

In this study, we outline an approach for estimating the size and frequency distribution of seismic events on tidally active worlds. 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 and apply the model to Europa.

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. This form of the equation assumes that eccentricity is not large (see e.g. [3]), whch is appropriate for Europa and other major icy satellites. 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. Eq. 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, Eq. 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 defined 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* ~ 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; however based on the seismic record detailed in Oberst [8] and the result from Nakamura [6], we adopt a *b* value of 0.5 for our Lunar constraint analysis.

Observations of the evolution of the Moon's pole of rotation by laser ranging implies strong dissipation within the Moon and constrains the value of k_2/Q to be 0.0012 [7]. This value yields a tidal dissipation rate of 1.18 GW, amounting to ~4x10^{16} J each year. Based on lunar seismicity reported in Apollo data from 1971-1976 by Oberst [8], the total seismic moment released is ~10^{15} Nm.

While studies tend to look at Lunar data on yearly periods, this timescale is somewhat arbitrary. For the Moon, a period of 1 year represents about 13 full tidal cycles. If we look at dissipation on the tidal timescale of 27.3 days, the total energy dissipated is ~3x10^{15} J. If the total seismic energy release and total moment release scales by the same factor then the total moment release, ΣM_o, is ~8x10^{13} Nm. Using a tabulation of events provided in Oberst [8] we find that an value of

$M_0^\star$=2.5x10^{14} Nm (M$_W$ 3.5) is needed to predict the correct number of seismic events (Fig. 1).

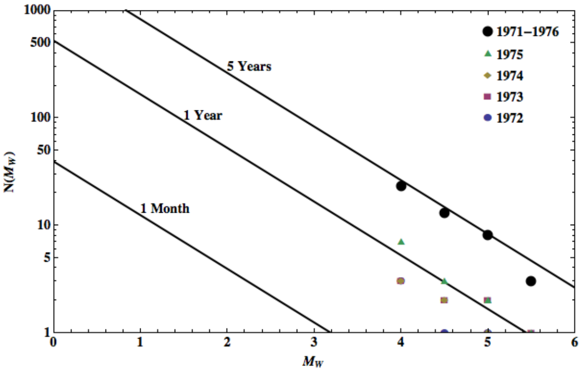

Figure 1. The Gutenberg-Richter relationship for Lunar events determined with b=0.5, ΣM_o=8x10^{13} Nm, and $M_0^\star$=2.5x10^{14} Nm evaluated for 1 Lunar cycle (1 month), a 1 year period, and for a 5 year period. The colored shapes represent tabulation of seismic data on yearly periods indicated, while the black dots represent the combined data spanning about a 5 year period.

We find that with the parameters used in the Lunar the assumed total seismic moment released in the tidal cycle that is based on the tidal energy dissipation (ΣM_o) is roughly equal to the sum of the seismic moments predicted by the Gutenberg-Richter distribution. Seismic moment is a proxy for seismic energy and implies that the seismic energy dissipated in the moon each orbital cycle is released in the same time interval by the sum of events driven by this dissipation.

Tidal dissipation and seismic energy: Models of Europa's interior and tidal response indicate a k_2/Q value of 0.0054 [9]. This value yields a tidal dissipation rate of 2.836 TW of energy and results in ~10^{20} J of energy each year, or ~10^{18} J per orbit. The same ratio between tidally dissipated energy and total seismic moment released on the Moon implies that ΣM_o is ~ 10^{16} Nm for Europa, per orbital cycle. For most terrestrial catalogs, b is close to 1, so in the absence of data, we assume that value for Europa. Finally, to balance the input and out of seismic energy over a single orbital cycle, as reflected in the sum of the moment of all predicted events, $M_0^\star$ is ~ 5x10^{16} Nm (M$_W$ 5).

The effect variation in the tidal dissipation rate over an orbit is estimated to increase seismicity rates by 14% at a quarter and three-quarters of an orbit, with a corresponding 14% decrease at pericenter and apocenter. Moreover, the rate of tidal dissipation spatially within Europa is not uniform. This heterogeneity can also affect the location of seismic events (Fig. 2).

Conclusions and Disscusion: If seismic observations can be made over several Europa cycles, it is reasonable to expect several events M$_W$ > 4 to occur. Based on this analysis, models of expected signal and background noise need to be updated. We will also explore how spatial and temporal variations can affect seismic detections. Finally, our model is generally applicable to any tidally flexed planetary body. It has implications for other tidally active bodes such as Io, Pluto, Charon, Phobos and exoplanets. It also has implications for seismic events on Titan [10], the target of the Dragonfly New Frontiers mission.

References: [1] Hurford et al. (2007), *Nature* 447 [2] Hedman et al. (2013), *Nature* doi:10.1038 [3] Wisdom (2008), *Icarus* 193, 637-640 [4] Golombek, M. P. et al. (1992), *Science*, 258, 979–981. [5] Panning et al. (2017), *JGR*, doi: 10.1002/2017JE005332, accepted. [6] Nakamura (1977), *Phys. Earth Planet. Int.*, doi:10.1016/0031-9201(77)90174-1 [7] Williams et al. (2001), JGR 106, 27,933-27,968 [8] Oberst, J. (1987), *JGR* 92(B2), 1397–1405. [9] Vance et al. (2007), Astrobiology 7, 987 [10] Panning et al. (2018) LPSC

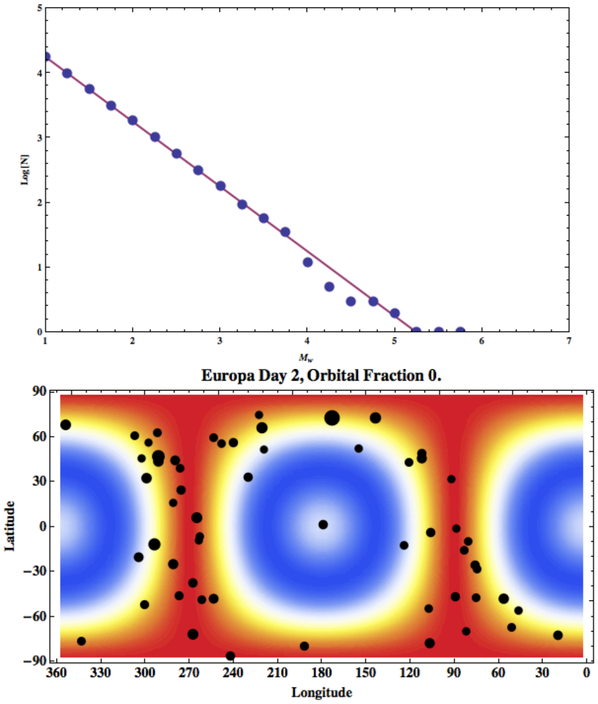

Figure 2: (Top) The Gutenberg-Richter relationship for Europa events determined for a 20 day period. The line represents the idealized case while dots show a stocastic determination. (Bottom) Seismic events predicted near pericenter of Europa's orbit are shown, the contours show the spatial distribution of the rate of tidal dissipation with warmer colors representing more tidal dissipation. Size of circle is proportional to magnitude.