REORIENTATION OF ICY SATELLITES DUE TO IMPACT BASINS. I. Matsuyama, *Dept. Terrestrial Magnetism, Carnegie Institute of Washington, (matsuyama@dtm.ciw.edu)*, F. Nimmo, *Dept. Earth & Planetary Sciences, U.C. Santa Cruz, Santa Cruz CA 95064 (fnimmo@es.ucsc.edu).*

Limited attention has been paid to reorientation of the icy satellites of the outer solar system. [1] investigated how redistribution of volatiles might affect the rotational stability of Triton and Pluto. [2] and [3] modelled reorientation due to convective processes on Miranda and Enceladus, respectively, and [4] pointed out that Europa's variable ice shell thickness might lead to rotational instability. Here we will focus on the fact, first pointed out by [5] for the Moon, that the negative long-term load caused by a large impact basin can potentially reorient a planetary body.

We will consider the specific case of a tidally-deformed satellite which has no initial rigidity, and is thus purely hydrostatic. As the satellite cools, it will develop a rigid lithosphere; at some point in the cooling process, the impact basin forms and reorientation, opposed by the fossil tidal and rotational bulges, will take place. Because of these bulges, the angular reorientation θ_R depends on the initial colatitude θ_L^f and longitude ϕ_L^f of the applied load. By diagonalizing the resulting moment of inertia tensor, the following set of equations may be derived [6]:

$$Q\sin^2\theta_L^f\sin(2\phi_L^f) = \sin^2\theta_R\sin(2\phi_R) - 3\sin^2\theta_T\sin(2\phi_T) \quad (1)$$

$$Q\sin(2\theta_L^f)\cos(\phi_L^f) = \sin(2\theta_R)\cos(\phi_R) - 3\sin(2\theta_T)\cos(\phi_T) \quad (2)$$

$$Q\sin(2\theta_L^f)\sin(\phi_L^f) = \sin(2\theta_R)\sin(\phi_R) - 3\sin(2\theta_T)\sin(\phi_T) \quad (3)$$

Here (θ_R, ϕ_R) and (θ_T, ϕ_T) are the coordinates of the initial rotational and tidal axes, respectively, and Q defines the size of the load. The initial tidal and rotational axes must be perpendicular, and the reorientation angle is given by θ_R.

For reorientation along the meridian passing through the tidal axis, these equations simplify to give $Q\sin(2\theta_L^f) = 4\sin(2\theta_R)$ while for reorientation along the meridian perpendicular to the tidal axis we obtain $Q\sin(2\theta_L^f) = \sin(2\theta_R)$. Thus, reorientation is larger if it occurs around the tidal axis, as expected [3].

The quantity Q describes the size of the load, and is given by [6]

$$Q = \frac{GM}{R^2}\frac{3\sqrt{5}G_{20}'^L}{R\Omega^2(k_f^{T*} - k_f^T)} \quad (4)$$

Here R,M and Ω are the satellite radius, mass and angular rotation frequency, G is the gravitational constant, $G_{20}'^L$ is the dimensionless degree-two gravitational potential of the load and k_f^{T*} and k_f^T are the tidal Love numbers of the body without and with an elastic lithosphere, respectively. Note that here we have assumed that the rotation rate is unaffected by the reorientation.

We will calculate the gravitational potential imposed by an impact basin as follows. For a basin having an angular radius ψ and a constant depth h, the normalized degree-2 potential when $h \ll R$ is given by [3]

$$G_{20}'^L = \frac{\pi h\rho R^2}{M}\cos\psi\sin^2\psi \quad (5)$$

where ρ is the surface density, and we are assuming that there are no other gravity anomalies present (e.g. a compensating mantle plug). The gravitational perturbation thus depends on the depth and angular size of the impact basin, as expected.

For simplicity, we have neglected the effect of the ejecta blanket and any central peak. The latter is unlikely to have a significant effect, as its mass is small compared with the total mass removed. The ejecta blanket, however, can reduce the effective potential anomaly, by a factor of ≈5 [5] if the blanket extends uniformly out to two basin radii and no material escapes the satellite. Scaling arguments [9] suggest that most ejecta is retained; however, the distribution of ejecta is hard to infer from Voyager-era data [7] and the quantity of material vapourized and thus permanently lost is unknown. Imaging by the *Cassini* spacecraft is likely to make the role of the ejecta clearer.

Equations (1)-(5) may be used to infer the reorientation caused by a given basin. To do so, we need to calculate the Love numbers k_f^{T*} and k_f^T. These will depend on the density and (for k_f^T) rigidity structures of the satellites, which are not in general well known. We will therefore make the conservative assumption that k_f^{T*}=1.5, the value for a homogeneous fluid body, and that k_f^T=0 (perfectly rigid). In this way, our estimate of the reorientation angle θ_R will be conservative.

Table 1 summarizes the location, diameter D and present-day maximum depth d_{max} of the impact basins we consider [7]. To be conservative, depth is defined as below the background elevation, rather than relative to the crater rim. Topographic profiles across these impact basins [7] suggest that they are generally flat-floored, and thus that our assumption of a constant-depth basin is reasonable. We therefore assume that $h = d_{max}$.

Figure 1 shows the polewards reorientation angle θ_R as a function of basin angular radius ψ and the centripetal acceleration of the satellite. The basin depth (2 km) and initial latitude ($\theta_L^f = 45°$) are kept constant and reorientation is assumed to occur around the tidal axis. As expected, larger basins lead to greater reorientation. Similarly, other things being equal, a satellite which is spinning faster experiences less reorientation, because the equatorial and tidal bulges are larger.

Table 1 tabulates the polewards reorientation θ_R expected for the real basin locations and depths. Herschel, because it is equatorial, produces almost no reorientation, despite its relatively large perturbation to the gravity field. Aeneas, being both shallow and relatively small, likewise produces little reorientation. Odysseus and Tirawa result in larger ($10.3°$ and $19.4°$, respectively) reorientations - the former because Odysseus is large, and the latter because Rhea is a slow rotator. For Titania, the nominal basin parameters resulted in no

Table 1: Impact basins

Body	R km	P days	Basin	Colat. θ_L^f	W. Lon. ϕ_L^f	D km	d_{max} km	ψ	Q	Δg mGal	θ_R
Mimas	196	0.942	Herschel	$87°$	$-111°$	135	11	$19.7°$	-0.85	-12.8	$2.5°$
Tethys	530	1.888	Odysseus	$60°$	$-130°$	450	3	$24.3°$	-0.50	-13.1	$10.3°$
Dione	560	2.737	Aeneas	$64°$	$-46°$	175	3	$9.0°$	-0.15	-2.1	$2.6°$
Rhea	764	4.518	Tirawa	$54°$	$-150°$	350	5	$13.1°$	-1.07	-8.6	$19.4°$
Titania	790	8.706	Gertrude	$107°$	$-68°$	400	2	$14.5°$	-1.85	no solution found	
Titania	790	8.706	Gertrude	$107°$	$-68°$	400	1.3	$14.5°$	-1.2	-3.0	$18.1°$
Pluto	1152	6.38	unknown	($45°$)	($-90°$)	(602)	(2)	($15°$)	(-0.73)	(-5.2)	($23.4°$)

Here R and P are the satellite radius and period, D and d_{max} are the basin diameter and maximum depth (from [7]), Q is the dimensionless load (equation 4), θ_R is the amount of poleward reorientation, Δg is the degree-2 gravity anomaly at 100 km spacecraft altitude, calculated from G_{20}^L using the method given in [3], and ψ is the basin angular radius. Satellite data obtained from [8] and we assumed $\rho = 900\ kg\ m^{-3}$. For Titania, a solution could not be obtained with the nominal basin parameters. It is not known whether Pluto has any impact basins; the calculations presented here represent an example assuming the basin dimensions are comparable to those of the other icy satellites.

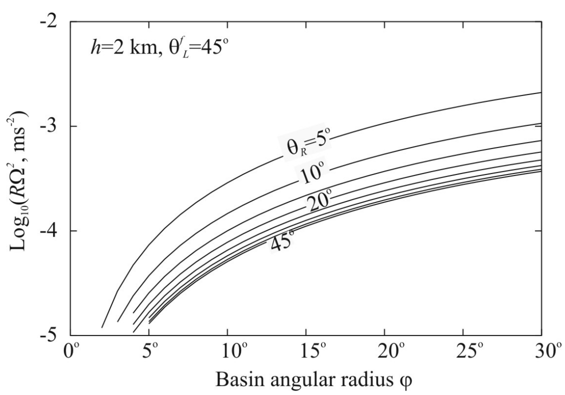

Figure 1: Polewards reorientation angle θ_R (plotted at $5°$ intervals) as a function of basin angular width ψ and satellite centripetal acceleration $R\Omega^2$, calculated using equations (1)-(5). Basin depth h=2 km, initial colatitude $\theta_L^f = 45°$; reorientation is assumed to take place around tidal axis (see text).

solution being found to equations (1)-(3). Reducing the basin depth gave a large reorientation ($18.1°$), primarily because of Titania's slow rotation.

Apart from the effect of an ejecta blanket, which is hard to quantify, the results presented in Table 1 will tend to underestimate the actual amount of reorientation. In particular, the relevant basin depth is that applicable as reorientation proceeded. Since reorientation and isostatic basin rebound occur on comparable timescales, the present-day basin depth is almost certainly an underestimate.

Our main conclusion is that, particularly for slow-rotating satellites, the presence of impact basins can lead to significant (tens of degrees) reorientation of these bodies. As with Enceladus [3], such reorientation is likely to have observable consequences. Perhaps most importantly, reorientation by tens of degrees will lead to stresses sufficient to cause fractures, and probably a global pattern of tectonic features [10]. Such patterns are likely to be present on both Rhea and Tethys, and may be revealed by existing or future *Cassini* observations. Secondly, the expected apex-antapex asymmetry in impact crater distribution [11] will be smeared out if reorientation occurs [e.g. 12]. Finally, the impact basins are associated with negative degree-two gravity anomalies, tabulated in Table 1, of order 10 mGal, which may be detectable with sufficiently close spacecraft flybys. These gravity anomalies are comparable to those expected from the rotational and tidal deformation of a fluid body [13]. Thus, determination of satellite structure using the gravity coefficients J_2 and/or C_{22} [14] is likely to be significantly complicated by the presence of these large (and presumably uncompensated) impact basins.

Pluto and Charon are both slow rotators and thus prone to reorientation. Although no impact features are currently known, it is likely that both bodies possess basins of comparable sizes to those listed in Table 1. Taking $\psi = 15°$ and using the same basin parameters as for Fig. 1, the reorientation angle for Pluto is $23.4°$. Thus, if Pluto or Charon possess impact basins comparable to those examined here, reorientation is very likely to have occurred.

References

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