TIDAL DISRUPTION OF INVISCID PROTOPLANETS. A.P. Boss[1], A.G.W. Cameron[2], & W. Benz[2]. [1]DTM, Carnegie Institution of Washington, 5241 Broad Branch Road N.W., Washington DC 20015. [2] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge MA 02138.

Roche showed that equilibrium is impossible for a small fluid body synchronously orbiting a primary within a critical radius now termed the Roche limit. Roche's static criterion has been extended to bodies with tensile strength [1], and has been used to argue that even bodies on hyperbolic orbits would be tidally disrupted within the Roche limit [10,11]. Tidal disruption of orbitally unbound bodies is a potentially important process for planetary formation through collisional accumulation, because the area of the Roche limit is considerably larger than the physical cross section of a protoplanet. Tidal disruption of unbound bodies is also the basis for the disintegrative capture model of lunar origin [10,11]. Because there is only a limited amount of time for tidal forces to act on an unbound body, a dynamic rather than a static analysis is required to determine the outcome.

Several previous studies have been made of dynamical tidal disruption. Protoplanets with strong dissipation (e.g., solid or partially molten bodies) do not undergo tidal disruption, even for grazing encounters [8,9]. The case for inviscid (e.g., molten) bodies, however, has been in dispute, with one model implying disruption within a modified Roche limit [7] and another disclaiming the possibility of disruption [5]. Another model followed the orbits of a hypothetically disrupted body [11], but did not include the body's self-gravity.

ANALYTICAL MODELS: Considerable insight into the dynamics of tidal disruption can be gained from a simple model based on comparing the velocity dispersion expected to be produced in a body by tidal forces with the escape velocity for segments of the body to be removed to infinity. While crude, this analysis does include the self-gravity of the body, which is the only agent capable of resisting tidal disruption in an inviscid body. We have considered three different models of disruption: (1) test particles leaving a sphere; (2) hemispherical breakup [6]; and (3) distortion of a cylinder of radius R_c and half-length R with $\epsilon = R_c/R$ being constant as $R \rightarrow \infty$. For each of these models, the criterion for tidal disruption is the same except for a factor c:

$$\left(1-\frac{R}{r_P}\right)^{-1/2} - 1 > \left(\frac{M}{cM'}\right)^{1/2}\left(\frac{r_P}{R}\right)^{1/2},$$

where primes denote the primary, r_P is the perigee radius, R is the protoplanet's radius, M is the protoplanet mass, and c is 1 for (1), 8 for (2), and ϵ for (3). In the limit of a small protoplanet ($R << r_p$), the criterion for case (1) becomes $r_P < 0.63R'(\rho'/\rho)^{1/3}$, which shows that a small protoplanet cannot be tidally disrupted in this approximation for $\rho' \sim \rho$; $r_P < 0.63R'$ requires a collision. Roche's criterion has a similar form but with a factor of 2.5 instead of 0.63.

The analytical criteria are plotted in Fig. 1. A massive protoplanet ($M/M' \rightarrow 1$) is tidally stable. For fixed protoplanet mass, as the perigee radius decreases, tidal disruption becomes possible if the protoplanet can disrupt before colliding with the primary. This can only occur for bodies less massive than $\sim 0.01 - 0.1 M_{\oplus}$. Fig. 1 also plots the masses and maximum ratios of protoplanet radius to perigee radius for the Earth, Mars, and the Moon. Unfortunately the smaller two of these bodies fall between the analytical curves for different assumptions, showing that a firm statement about the maximum mass for inviscid tidal disruption cannot be made through these crude models.

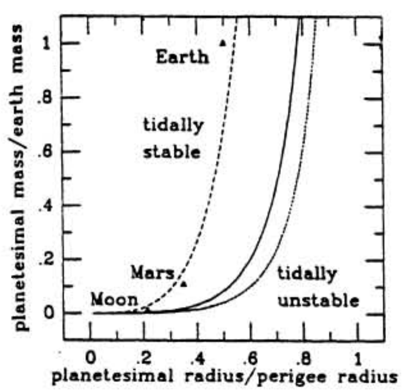

Fig. 1. Analytical prediction for tidal disruption or tidal stability of different mass, inviscid protoplanets on parabolic orbits about the Earth. Criteria for several plausible models of tidal disruption are shown: (1) solid line — test particle, (2) long dashed line — two pieces, and (3) short dashed line — cylinder with $\epsilon = 1/2$. Three representative planets are shown at grazing incidence; for larger perigees, these points move horizontally left, into the tidal stability regime. Large protoplanets are always stable by these criteria.

NUMERICAL MODELS: Because of the limitations of these analytical models, we have used a smoothed particle hydrodynamics (SPH) code to model the tidal disruption process.The code is basically the same as the one used to model giant impacts [2]; here we simply choose impact parameters large enough to avoid collisions. The primary and secondary both have iron cores and silicate mantles, and are initially isothermal at a molten temperature. Previous lunar formation calculations with the SPH code have shown that inviscid, Mars-sized bodies do not suffer tidal disruption by the Earth, even during glancing collisions, so we have restricted our models to lower mass protoplanets, specifically $0.01M_\oplus$. Two parameters have been varied (Table 1), the distance (r_P) between the two centers of mass at closest approach, and the velocity at infinity (v_∞). Because of the boring nature of non-disruption models, our models have focused on parameters that do lead to tidal disruption. Each protoplanet initially contained 3500 particles. Detailed plots of the time evolution of several of the numerical models will be shown during the oral presentation.

Table 1. Numerical results for inviscid $0.01M_\oplus$ protoplanets passing the Earth:

model	r_P ($R_\oplus$)	v_∞ (km/sec)	collided particles	inside Roche	outside Roche	escaped particles	escaped clusters
ah03	1.338	0	1675	11	0	1814	7
ah14	1.431	0	1188	35	0	2277	6
ah06	1.525	0	975	8	3	2514	5
ah07	1.711	0	485	15	0	3000	1
ah09[1]	1.897	0	972	145	816	1567	1
ah11[1]	2.084	0	324	387	1441	1348	2
ah01	1.337	2	1187	5	0	2308	3
ah17	1.430	2	839	2	0	2659	4
ah04	1.522	2	533	2	1	2964	3
ah08[2]	1.709	2	411	3	1	3085	5
ah10[2]	1.895	2	132	1	5	3362	2
ah16	2.082	2	0	0	0	3500	1
ah05	1.334	5	0	0	0	3500	7

[1] For ah09, 3172 particles were in a single cluster with apogee 350 $R_\oplus$ and perigee 1.8 $R_\oplus$. For ah11, 3450 particles were in a single cluster with apogee 110 $R_\oplus$ and perigee 1.9 $R_\oplus$. For both models, these clusters were assumed to be tidally disrupted on subsequent encounters (the numbers assigned to the various bins are therefore somewhat arbitrary). If v_∞ had been marginally > 0 for these models, these clusters (as well as other particles) would have escaped. Including the presence of the sun, the ah09 cluster would have escaped even with $v_\infty = 0$.

[2] The larger number of escaping clusters for these models compared to the models with $v_\infty = 0$ appears to be due to mass shedding [3], caused by the tidal torques being more efficient (more favorable phase angle) for the higher v_∞ models.

CONCLUSIONS:

* Protoplanets with masses greater than $\sim 0.1\ M_\oplus$ do not suffer tidal disruption, even for grazing incidence, parabolic orbits.
* Smaller mass ($\sim 0.01M_\oplus$) inviscid protoplanets will be at least partially tidally disrupted if $r_P < 1.5R_\oplus$ for $v_\infty > 2$ km s^{-1}.
* Up to half of the mass of a 0.01 $M_\oplus$ protoplanet may impact the Earth if $v_\infty \leq 2$ km s^{-1} and $r_P < 2R_\oplus$. However, very little mass is captured in Earth orbit.
* Because typical protoplanets in the late phases of terrestrial planet accumulation are thought to have had $v_\infty \sim 10$ km s^{-1}, tidal disruption was probably rare [5,8,9].
* Tidal torques are efficient at producing rotational spin-up, rotational instability, and mass shedding.
* Lunar formation through tidal disruption of a single protolunar body and capture of the debris into Earth orbit [10,11] appears impossible, and through multiple bodies very unlikely. Tidal disruption only occurs for relatively small bodies, and very little of their mass is injected into orbit. Orbital capture of a lunar mass would require many events, all favorably aligned, as well as having $v_\infty \sim 0$, both of which are unlikely [4]. Lunar formation following a giant impact appears to be preferable [2].

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