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SHOEMAKER-LEVY 9 AND THE TIDAL DISRUPTION OF COMETS W. Benz, University of Arizona; and E. Asphaug, NASA Ames Research Center

The break-up of Periodic Comet Shoemaker-Levy 9 into multiple pieces following its grazing encounter with Jupiter in July 1992 can be used to study tidally-induced fracture in comets. This spectacular event allows us not only to set limits on the size, strength and density of Shoemaker-Levy 9 itself, but provides invaluable guidance to numerical modeling of such encounters.

In an extensive treatment of tidal breakup which assumed self-gravitating, homogeneous, perfectly elastic bodies, Dobrovolskis [1,2] derived simple analytical expressions for the tidally-induced surface and central stresses. Both can be cast in such a way that Poisson's ratio is the only material dependent constant entering in these expressions. For various cometary radii, densities and Poisson's ratios, we compute upper limits to the comet's tensile strength for either surface or central fracture. Fig. 1, computed for a closest approach distance of $1.3R_J$ and a cometary radius of 5 km, displays both upper limits to the tensile strength of the comet as a function of its density. For both stresses we found the two Poisson ratios ($0 \leq \nu \leq 0.5$) that maximized and minimized our upper limits. These two curves for both central and surface strength are shown on Fig. 1. Since all materials have Poisson ratios between 0 et 0.5, the space between the curves can be seen as uncertainties in the derivation of our upper limits due to unknown cometary material properties.

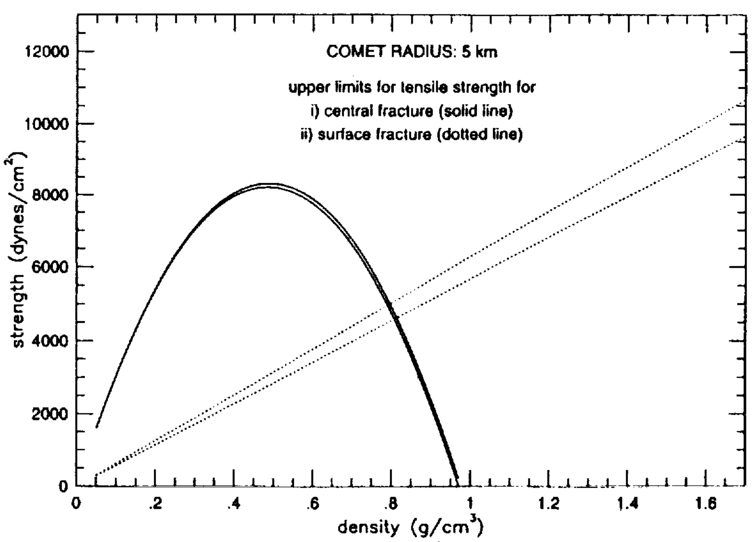

Fig. 1

For densities higher than 0.8 g/cc, fracture starts on the surface, whereas for lower densities, fracture initiates at the center. Note that the greatest strength still resulting in central fracture is strongly peaked at a density of about 0.5 g/cc, as denser comets are shielded by self-gravity and lower-density comets do not build up tidal stresses as high. Thus, if comets come with a large distribution of intrinsic strength, the ones most likely to be tidally disrupted are those with a density near 0.5 g/cm^3. The linear increase in the upper strength limit for greater density comets is the result of the linear dependence of tidal force on cometary mass. For comparison purpose, the tensile strength of water ice[2] in laboratory samples is 2×10^7 dynes/cm^2 or 2500 larger than our upper limit for central fracture. However, if one accounts for the fact that strength of an object scales[3] like $R^{-\alpha}$ with $0.5 \leq \alpha \leq 0.24$, we obtain a corresponding strength for a 5km pure ice block of 8.9×10^4 or 1.5×10^6 dynes/cm^2 depending on α (for an assumed laboratory sample of 10 cm). These numbers are still between 10 to 190 times larger than our upper limits.

Whether both surface and central failure must be initiated as a criterion for breakup, or either one of them is sufficient, remains a subject of disagreement. To resolve this debate, we model the details of cometary breakup using a three-dimensional Smooth Particle Hydrodynamics (SPH)[4] code modified to simulate fracture in small solid objects[5]. At the lower stresses associated with brittle failure, we use a rate-dependent strength based on the nucleation of incipient flaws whose number density is given by a Weibull distribution. These flaws nucleate fracture once a local strain threshold has been exceeded. The effect of growing cracks on the dynamics is described by a new state variable D ("damage")[6], $0 \leq D \leq 1$ which affects the stress tensor in such a way that a totally damaged region cannot sustain any tensile or shear stress.

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This scheme was extensively tested on numerous analytical and experimental results with great success. For example, our code is only one currently available correctly predicting central cores of the appropriate mass laboratory impact experiments[5].

Figure 2 illustrates the outcome of the two modes of fracture. We plotted velocity vectors at particle locations in a narrow equatorial slice for a case where fracture initiates on the surface (left panel) and in the center (right panel). As can be seen from this Figure, surface fracture results in a slow erosion of the outer layers on the near and far side of the comet, whereas central fracture actually breaks the comet into 2 hemispheres. From these results, we conclude that in order for an object to be broken up into many sizeable fragments, fracture has to initiate in the center. Indeed, surface fracture by eroding the near and far side of the object actually reduces the size over which tidal stresses can act, thus effectively shielding the inner parts from further disruption.

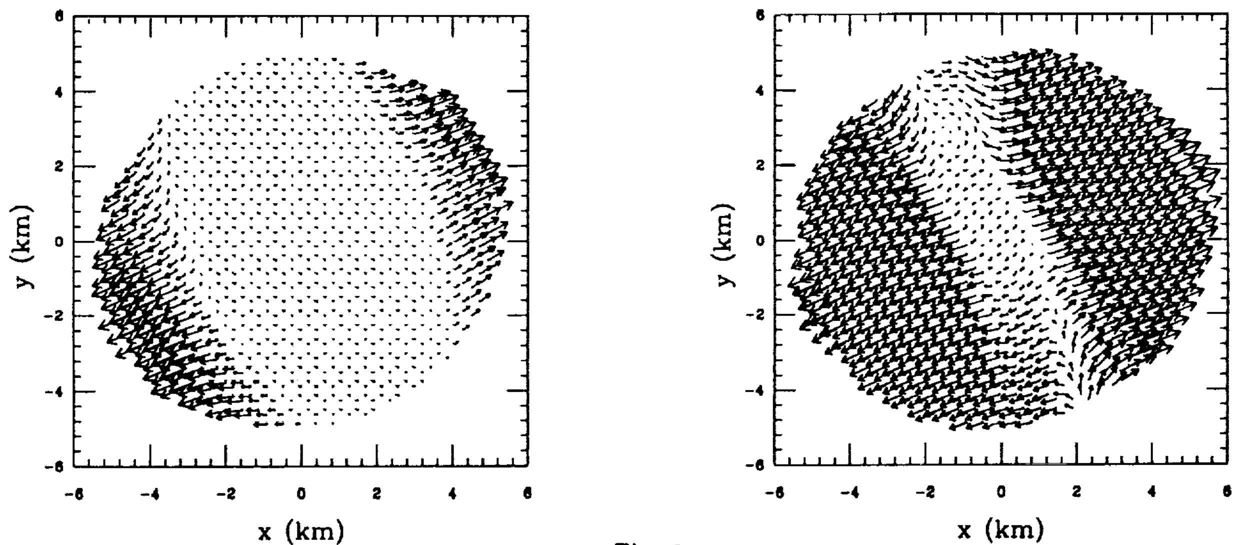

Fig. 2

Using the requirement that fracture has to initiate in the central region together with Fig. 1, implies a very strict upper bound for comet Shoemaker-Levy's density of 0.8 g/cm^3. It is important to recall that our upper limits for both strength and density are very conservative ones. Indeed, we assumed in deriving these numbers that breakup occurred at closest approach and that all the fragments can be obtained in one episode of fragmentation. Thus, we argue that although the radius of comet Shoemaker-Levy might be quite large (5km), the mass involved may not be that large owing to the low density of the material.

These results have been obtained assuming the comet is made of a homogeneous material and obeys the usual laws of elasticity as a single object. Clearly, this may not be the case as for example, if comets are made out of a collection of loosely bound smaller entities, then fracture initiates at the boundaries between these "cometesimals" and the comet breaks up into a subset of the original fragments. We are currently investigating numerically the breakup of these heterogeneous comets.

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