THE BREAKUP OF COMET C/2012 S1 (ISON) THROUGH DIFFERENTIAL SUBLIMATION PRESSURE.

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Introduction: Comet C/2012 S1 (Comet ISON) made its perihelion pass only 0.01244 AU ($2.7R_{\odot}$) from the center of the sun on the 28 November, 2013 [1]. Comet ISON was observed by the STEREO and SOHO spacecraft, from which the comet appeared to breakup up ~4-5 hours before perihelion. This corresponds to a heliocentric distance of ~5-6 $R_{\odot}$, which is outside both the fluid and rigid body Roche limit of the sun, where tidal stresses are strong enough to disrupt a body.. Sun-grazing comets can also be disrupted through ablative and explosive mechanisms as the comet travels through the sun's atmosphere, however these mechanisms cannot explain the breakup of Comet ISON because its perihelion distance is larger than $1.01R_{\odot}$ [2].

We propose instead that the difference in pressure of sublimating gas on the surface of the sunward side and the dark side of the comet rises to overcome the nucleus' own tensile strength, causing catastrophic breakup the nucleus (see Figure 1). We first estimate the dynamic pressure that sublimating ice exerts on the illuminated hemisphere of ISON's nucleus as a function of heliocentric distance. We then compare the pressure to estimates of cometary strength to estimate at what heliocentric distance the comet would be expected to break up.

Estimating Dynamic Pressure: We estimate the dynamic pressure exerted on the surface of the comet by the sublimation of major volatiles: H_2O, CO_2, and CO. We model the nucleus as an ice sphere and assume that all absorbed incident energy goes toward sublimating volatile ices near the surface, ignoring the amount of energy going toward warming the ices, which we estimate to be at most ~10%, ~30%, and ~30% of the energy needed to overcome latent heat of sublimation for H_2O, CO_2, and CO respectively. We also assume that the surface of the comet absorbs all incident radiation (albedo of zero). We model the rate of insolation by assuming the sun to be a point source, and then determine the intensity of the solar radiation at the location of the breakup of the nucleus. We further assume that gas emission occurs only on the illuminated hemisphere of the cometary nucleus, consistent with the observed low thermal inertias of cometary nuclei [3][4]. This leads to the assumption of zero dynamic pressure on the dark side of the nucleus.

These assumptions allow us to estimate mass-loss rates for H_2O, CO_2, and CO based on heliocentric distance. We then use these mass-loss rate estimates along with the Clausius-Clapyron criterion and the mass-loss rate equation in [5]

$$P_{(T)} = P_0 e^{-\frac{\lambda}{RT}}$$

$$\dot{m} = \sqrt{\frac{m_{mol}}{2\pi RT}} P_{(T)}$$

to estimate the surface temperature, where m_{mol} is the molar mass of the species, T is the temperature, R is the ideal gas constant, λ is the species' latent heat of sublimation, and P_0 is a constant defined by a known temperature and pressure. From the temperature, we calculate the thermal velocity and resulting momentum flux between the sublimating gas and comet nucleus for each of the major volatile species.

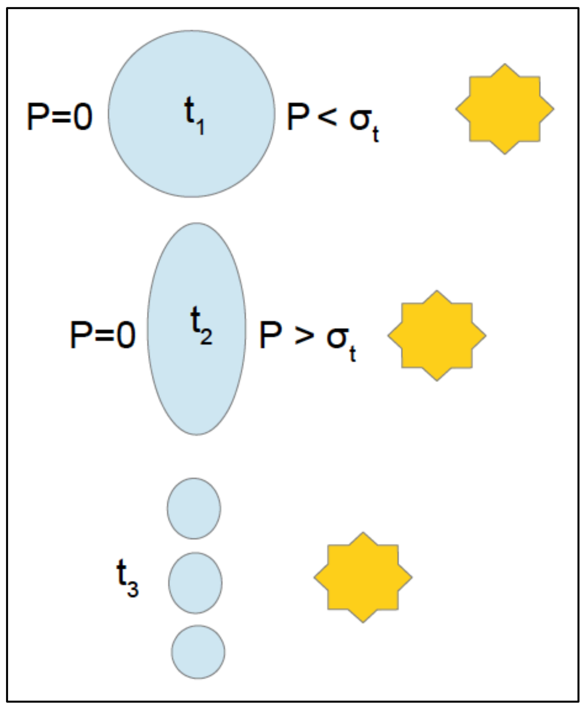

Figure 1: A cartoon illustrating the dynamic pressure breakup. We assume dynamic pressure to be zero on the dark side of the nucleus, while the pressure on the illuminated side (P_{dyn}) is compared to the tensile strength of the comet (σ_t). When P_{dyn} becomes greater than σ_t the nucleus can disrupt catastrophically.

Results: The dynamic pressure versus heliocentric distance for CO, CO_2, and H_2O is plotted in Figure 2, which shows that H_2O-dominated sublimation reached dynamic pressures that were strong enough to disrupt the nucleus at a heliocentric distances of ~5 $R_\odot$ (corresponding to ~4 hours before perihelion), based on an estimated cometary tensile strength of 270 Pa [6]. However, other strength estimates of <100 Pa [7], and <6.5 Pa [8] place the disruption at heliocentric distances of >7 $R_\odot$. If CO_2 or CO is the dominant sublimating species, then these distances would be greater still.

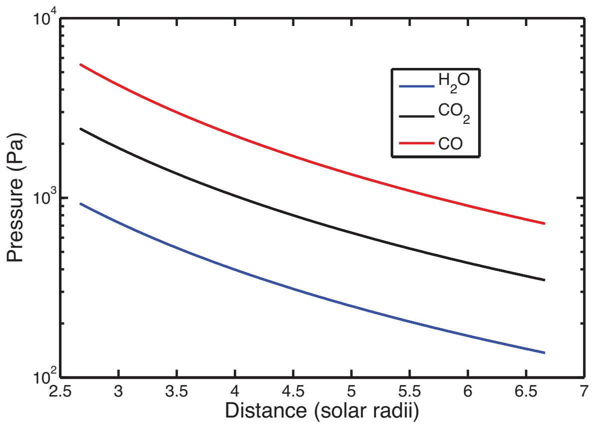

Figure 2: A plot of our calculations of the dynamic gas pressures for spheres of pure H_2O, CO_2, and CO as a function of heliocentric distance. Were there to be a mixture of volatile species, then the dynamic pressure curve would lie in between the pressure curves of the respective species. A dynamic pressure curve for silicates would lie below our plotted area.

Isostatic Pressure. It is important to note that the isostatic pressure within the cometary nucleus itself is not important if material strength dominates. For a spherical nucleus with a density of 500 kg m^{-3} that is 600 m across [9] we calculate a maximum isostatic pressure (at the center of the body) of 3.1 Pa. This value is far lower than the strength estimates in [6] and [7], but is comparable to the estimate in [8]. However, if this mechanism is to be a plausible explanation of the breakup of Comet ISON, then ISON's nucleus needs to have a strength that is significantly greater than in [8], rendering isostatic pressure irrelevant.

Discussion: The observation that Comet ISON broke up at a heliocentric distance of ~5-6 $R_\odot$ suggests H_2O is responsible for most of the dynamic pressure, based on the 270 Pa strength estimate in [6]. However, one must be careful to realize that this is the point at which ISON was observed to have been broken up. This does not mean that the comet had not started to fragment at a greater heliocentric distance. In addition, since many cometary strength estimates are significantly lower than 270 Pa, it would be reasonable if the comet had broken up at heliocentric distances of 8 $R_\odot$ or greater.

At these greater heliocentric distances, CO_2, which is more volatile that H_2O, becomes comparable to the cometary strength estimates. However, Comet ISON was observed to be very water rich as it approached the sun, with production rates on the order of q_{water} = $2x10^{30}$ s^{-1} on Nov 21.6-23.6 [10]. This measurement is consistent with our mass-loss estimates of ~$1.5x10^{30}$-$4x10^{30}$ for a 400-600 m nucleus at the corresponding heliocentric distance. This suggests that H_2O is indeed the species of interest for this breakup mechanism. This implicitly suggests that sun-grazing comets that survive perihelion have either low volatile production rates or very high strength.

Our assumption that gas emission occurs only on the sunward side biases our results in the direction of requiring greater cometary strengths. In reality, gas emission likely occurs on the dark side of the comet as well, counteracting some of the pressure exerted on the sunward side of the nucleus. This means that less strength is required to resist the sunward side pressure, allowing the comet to reach smaller heliocentric distances before disrupting.

Conclusion: We have shown that a breakup mechanism through gas-nucleus momentum transfer is able to overcome the strength of the cometary nucleus at the right heliocentric distances to match observations. Furthermore, our model suggests that H_2O is the volatile species that would be important in disrupting the nucleus of ISON, which is consistent with the observations that ISON is water-rich [10].

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