WILL COMET ISON (C/2012 S1) SURVIVE PERIHELION?

MATTHEW M. KNIGHT\textsuperscript{1,3} AND KEVIN J. WALSH\textsuperscript{2}

\textsuperscript{1}Lowell Observatory, 1400 West Mars Hill Road, Flagstaff, AZ 86001, USA; knight@lowell.edu
\textsuperscript{2}Southwest Research Institute, 1050 Walnut Street, Suite 400, Boulder, CO 80302, USA

Abstract

On 2013 November 28 Comet ISON (C/2012 S1) will pass by the Sun with a perihelion distance of 2.7 solar radii. Understanding the possible outcomes for the comet's response to such a close passage by the Sun is important for planning observational campaigns and for inferring ISON's physical properties. We present new numerical simulations and interpret them in context with the historical track record of comet disruptions and of sungrazing comet behavior. Historical data suggest that sizes below \(\sim 200\) m are susceptible to destruction by sublimation driven mass loss, while we find that for ISON's perihelion distance, densities lower than 0.1 g cm\(^{-3}\) are required to tidally disrupt a retrograde or non-spinning body. Such low densities are substantially below the range of the best-determined comet nucleus densities, though dynamically new comets such as ISON have few measurements of physical properties. Disruption may occur for prograde rotation at densities up to 0.7 g cm\(^{-3}\), with the chances of disruption increasing for lower density, faster prograde rotation, and increasing elongation of the nucleus. Given current constraints on ISON's nucleus properties and the typically determined values for these properties among all comets, we find tidal disruption to be unlikely unless other factors (e.g., spin-up via torquing) affect ISON substantially. Whether or not disruption occurs, the largest remnant must be big enough to survive subsequent mass loss due to sublimation in order for ISON to remain a viable comet well after perihelion.

Key words: comets: general – comets: individual (C/2012 S1 ISON) – methods: numerical – planet–star interactions

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1. INTRODUCTION

Comet ISON (C/2012 S1) was discovered on 2012 September 21 and will reach perihelion on 2013 November 28 at a sungrazing distance of 0.0125 AU = 2.7 solar radii (\(R_\odot\); Novskii & Novichonok 2012). The lead time of more than one year from discovery until perihelion is unique in sungrazing comet history and allows unprecedented planning of ground- and space-based resources in order to maximize the scientific return. While ISON's orbit is well known, the likely result of its perihelion passage is not, prompting this Letter.

Understanding the possible outcomes for the comet’s response to such a close passage by the Sun is important for a variety of reasons. First, ISON is much better placed for Earth-based observations post-perihelion than pre-perihelion, so most intensive observational campaigns are planned for after perihelion. If ISON is unlikely to survive then all efforts should be made to obtain data prior to perihelion. Second, ISON is expected to be observable by the fleet of space-based solar observatories, most of whom have limited real-time flexibility in their observations; early predictions of ISON’s behavior will help them optimize their observing sequences. Third, it has recently become possible to use comets as probes of the solar environment (Schrijver et al. 2012; Bryans & Pesnell 2012; Downs et al. 2013). These studies require basic assumptions about the physical nature of the comet; in order to properly interpret these data, it is critical to understand whether ISON behaves differently than the two previous comets utilized in this manner.

As detailed in the remainder of Section 1, there are numerous studies of tidal encounters of comets and asteroids with planetary bodies, and a historical track record of sungrazing comets being destroyed by disintegration and/or disruption. We use these as a guide and conduct numerical simulations of ISON’s perihelion encounter in Section 2. Finally, in Section 3 we interpret these simulations and make reasonable assumptions about ISON’s nuclear properties in order to determine the range of likely outcomes and the comet’s chances of surviving perihelion.

1.1. Tidal Disruption

Disruptions of solar system bodies due to tidal forces can be spectacular, with Comet Shoemaker–Levy 9 (henceforth SL9) a prime example. While Roche (1847) theorized about the disruption of fluid bodies on circular orbits with synchronized spin states, SL9 and other recent discoveries have motivated more sophisticated studies of different types of encounters and more realistic models of internal structure.

Oort cloud comets typically have nearly parabolic encounters with the Sun, which is a vastly different geometry than that envisioned by Roche (see also Chandrasekhar 1969). Similarly, a large body of work based on decades of observations and numerical simulations has painted a picture of small solar system bodies as “rubble piles,” again vastly different than the liquids considered by Roche or Chandrasekhar (see also Richardson et al. 2002 for a review). These gravitationally bound bodies are typically assumed to have zero or possibly very limited tensile strength, and therefore may rely only on their self-gravity to bind them and the shear strength afforded by their building blocks’ physical sizes to resist re-shaping. In fact, it was the breakup of comet Ikeya-Seki in 1965 (Sekanina 1966, and references therein) during its sungrazing passage that prompted Opik (1966) to suggest that it may have been a “heap of rubble.”

Prior to the discovery of SL9, work was underway to extend the calculations of Roche to a more diverse set of circumstances.
Boss et al. (1991) used smoothed particle hydrodynamics simulations to model inviscid planetesimals passing close to Earth, finding that the increase of the planetesimal’s spin angular momentum during the encounter can induce equatorial mass-shedding. Sridhar & Tremaine (1992) extended the analytical work into the regime of viscous-fluid bodies having parabolic encounters with a planet, finding that mass shedding begins at ∼69% of the classical Roche limit in this scenario.

The discovery of SL9 in 1993 launched significant numerical modeling efforts of tidal disruption outcomes. Specifically, N-body gravitational codes were employed to model gravitationally bound “rubble pile” bodies’ constituent pieces. In seeking a match to the precise morphology observed in the SL9 fragment chain, Asphaug & Benz (1996) identified many important and challenging degeneracies in the tidal breakup process. While the “strength” of the breakup increased with decreasing density and increasing prograde spin rate, the trade off between density and spin rate was very clean—there is no simple way to break that degeneracy. Richardson et al. (1998) went further and explored the effects of shape during a tidal encounter, finding that elongated bodies can disrupt even more violently, but in a manner that is very dependent on the orientation of their long axis at the time of close approach. Recent work for the SL9 disruption has found that using non-spherical particles for the rubble pile progenitor frustrates disruption somewhat (Movshovitz et al. 2012), suggesting that hard spherical particle models (as presented here) may represent an upper limit for disruption parameters.

However, there are numerous examples of cometary breakups that do not fit neatly into any of the previous “rubble pile” models, including nearly all of those that suffered disruption far from perihelion or any other known perturbations (e.g., Boehnhardt 2004). These events remind us that while models might predict only a modest re-shaping or very weak tidal forces acting across a body, it might only need to “light a fuse” inside a comet leading to a later disruption.

There are substantial uncertainties in modeling a cometary disruption near the Sun. Specifically, the extensive modeling of the SL9 event presented in Asphaug & Benz (1996) inferred very low or zero tensile strength to best explain the observations, but Holsapple & Michel (2008) demonstrated that even very small amounts of tensile strength can have a dramatic effect on disruption limits, especially at ∼km sizes. While tensile strength is very hard to measure, it was inferred for 9P/Tempel 1 from the Deep Impact experiment as being considerably weaker than heavily fractured ice, but non-zero (Richardson et al. 2007; Holsapple & Housen 2007). However, given the extremely high evaporation rates during perihelion, there are other forces that may exceed any small values of tensile strength. An example demonstrated by Gundlach et al. (2013) finds that the forces created during the outgassing of ices on a sungrazing comet may be strong enough that the reaction force on the nucleus delays or prevents tidal splitting.

Complications aside, for ISON’s perihelion distance, the classical Roche limit predicts mass loss for densities <1.03 g cm⁻³, while Sridhar & Tremaine (1992) predicts mass loss for densities <0.34 g cm⁻³. Holsapple & Michel (2008) predicts mass loss for densities <0.13 g cm⁻³ for a non-spinning spherical cohesionless rubble pile with a 40° angle of friction, while a similar body with a lower angle of friction (20°) would only need a density <0.27 g cm⁻³. Though “disruption” is defined differently in each work, all estimated comet densities have been <1.0 g cm⁻³ (Weissman et al. 2004; A’Hearn 2011), so ISON clearly warrants further investigation.

Historically, the term “sungrazing” was applied exclusively to members of the Kreutz family (Kreutz 1888; discussed below). When Solar and Heliospheric Observatory began discovering non-Kreutz comets in small-perihelion distance (q) orbits, “sungrazing” and “sunskirting” began to be used to distinguish the Kreutz from the larger-q near-Sun comets, but without being formally defined. Rather than dividing at some arbitrary distance, we propose to give it a physical basis by using the Roche limit, which can be calculated easily if one measures the comet’s density or can safely assume a nominal value. This limit distinguishes between comets that may suffer tidally driven mass loss (sungrazers) from those that will not (sunskirters). With this definition, the only ground-observed comets classified as sungrazers that are not Kreutz comets are C/1680 V1 and ISON (Marsden & Williams 2008).

1.2. Previous Disruptions of Sungrazing Comets

Observational constraints on the behavior of sungrazing comets near perihelion come entirely from the well known Kreutz group. Kreutz comets have q = 1–2 R⊙ and orbital periods of 500–1000 yr. They are dynamically linked to a single progenitor, with the members having been produced by cascading fragmentation over several orbits (cf. Marsden 1967, 1989; Sekanina & Chodas 2007). The group consists of a smattering of naked-eye comets seen over several centuries plus a nearly continuous stream of faint comets observed only with space-based coronagraphs.

The coronagraphically discovered Kreutz comets do not survive perihelion; in fact, they typically peak in brightness at 10–15 R⊙ then rapidly fade (Biesecker et al. 2002; Knight et al. 2010). Four Kreutz comets—C/1880 C1, C/1887 B1, C/1945 X1, and C/2011 W3 (Lovejoy)—survived until or shortly after perihelion, often appearing as headless tails receding from the Sun, while five—C/1843 D1, C/1882 R1, C/1963 R1, C/1965 S1 (Ikeya-Seki), and C/1970 K1—clearly survived (Sekanina 2002; Kronk 2003, 2009; Kronk & Meyer 2010; Sekanina & Chodas 2012). Other than C/1970 K1, all that clearly survived were observed to split during the perihelion passage, with at least one substantial remnant surviving and exhibiting cometary behavior for an extended time.

Thus, the Kreutz comets demonstrate the range of outcomes that may befall ISON. The smallest comets, consistently estimated to be <0.2 km in radius (e.g., MacQueen & St. Cyr 1991; Raymond et al. 1998; Sekanina 2003; Knight et al. 2010) succumb to sublimation driven mass loss during the perihelion passage. Intermediate sized comets, 0.2–1.0 km in radius, are large enough to survive mass loss due to sublimation (Iseli et al. 2002; Sekanina 2003), but likely disrupt with no individual fragment sufficiently large to remain a viable comet significantly beyond perihelion. The largest comets (radius >1 km) easily survive sublimation driven mass loss alone and, even if they fragment, remain viable comets that will return on a subsequent perihelion passage.

1.3. Comet ISON

Despite its sungrazing orbit, ISON is not a member of the Kreutz group; it is a “dynamically new” comet entering the solar system for the first time (as evidenced by its reciprocal original semi-major axis of 7×10⁻⁶ AU⁻¹), whereas the Kreutz comets have made at least several sungrazing orbits over the last few thousand years. There are expected to be differences in the outer layers of dynamically new comets as compared to returning comets due to the former’s long residence in the
Oort cloud (cf. Stern 1990). While we use the Kreutz comets as a guide out of necessity, this differing evolutionary history may result in compositional or structural differences that affect ISON’s survivability.

As discussed in the preceding subsection, the first criterion for ISON to survive perihelion is its nuclear size. Hubble Space Telescope (HST) observations set an upper limit on the radius of ~2 km (Li et al. 2013). We estimate the minimum radius to be ~0.4 km using the only published gas measurements (Schleicher 2013a, 2013b) and following the methodology of Cowan & A’Hearn (1979, using M. A’Hearn’s web-based calculator4). Similar calculations using the estimated production rates of CO or CO₂ from Spitzer Space Telescope images (Lisse et al. 2013) and upper limits of CO from HST spectroscopy (M. A’Hearn, private communication) yield minimum radius estimates of 0.1–0.3 km.

This range of possible nuclear sizes suggests that, based on the behavior of Kreutz comets, ISON is likely large enough to survive mass loss due to sublimation alone, but not necessarily so large that some fragment(s) would reasonably be expected to remain viable if the nucleus disrupts. Note that ISON’s perihelion distance is slightly larger than that of the Kreutz family so it will likely suffer less sublimation driven mass loss; however, for simplicity, we assume it has the same survival thresholds. Therefore, in order to estimate ISON’s chances of survival, we need to investigate its susceptibility to tidal disruption.

2. SIMULATIONS

The history of cometary disruption and fragmentation is strongly suggestive of forces beyond gravity playing a significant role (e.g., C/1999 S4 LINEAR, 73P/Schwassmann-Wachmann 3). However, we aim to build a baseline for the expected behavior of ISON during its perihelion passage strictly due to the tidal forces. From this baseline, with historical perspective and the best possible estimates of important unknown variables, we make a prediction about its behavior at, and immediately following, perihelion.

Richardson et al. (1998) explored a range of shape and spin combinations and a wide range of close encounter distances and hyperbolic encounter characteristics for close passages of rubble-pile asteroids to the Earth. Here, the encounter parameters are known with significant accuracy, and the encounter is nearly parabolic. Given that this specific encounter is of great interest, and velocity at infinity \( v_\infty \) = 0 km s\(^{-1}\) (e.g., a comet arriving from the Oort cloud) was not explicitly tested in Richardson et al. (1998), we endeavor to explore more deeply the possible outcomes for \( q = 2.7 R_\odot \) and \( v_\infty \sim 0 \text{ km s}^{-1} \), focusing on the effects of internal density, spin, and shape of the body.

Our simulations were designed to test a parabolic flyby of a gravitational aggregate, and used the \( N \)-body code pkdgrav (Richardson et al. 2000). The progenitor bodies were constructed of ~2000 hard spherical particles that were initially in a close-packed configuration. The encounters were started at \( 10 R_\odot \) and continued until the re-accumulation of fragments was considered to be complete—typically 10,000–20,000 timesteps, each of ~50 s. Starting the simulations earlier or running them later has no effect on the results (Walsh & Richardson 2006). As will be described below, bulk densities were explored in the range of 0.075–0.8 g cm\(^{-3}\), and two shapes were explored, a sphere and a body with 2:1:1 axis ratios rotating uniformly around its short axis (the elongated body is near the extreme axis ratios observed for comets and should represent an end-member case of all the possible shapes).

The rotation rate selected for the prograde encounters was taken to be 50% of the critical rotation rate (the rate at which mass begins to be lost due to centrifugal acceleration), following the simplistic formulation

\[
P_{\text{crit}} = \frac{3.3 \text{ hr}}{\sqrt{\rho}} \sqrt{\frac{a}{b}},
\]

where \( P_{\text{crit}} \) is the rotation period corresponding to the critical rotation rate, \( \rho \) is the density of the body in g cm\(^{-3}\), and \( a \) and \( b \) are the long and intermediate axis lengths respectively (using the same notation as in Richardson et al. 1998). While the selection of this rotation rate was somewhat arbitrary, much more rapid rotation would dramatically increase the chances of disruption and such fast rotation rates are rare among comets. Thus for a spherical body \( (a = b) \) with \( \rho = 0.5 \text{ g cm}^{-3} \), \( P_{\text{crit,50%}} = 9.33 \text{ hr} \). For the same densities but an elongated body \( (a = 2 \times b) \) the rotation periods were a factor of \( \sqrt{2} \) longer.

For the baseline simulations with non-rotating (which is akin to a very long rotation period in these simulations) or prograde rotating spherical bodies, 10 simulations for each density were run to account for any geometry inherent in the close-packed configuration of the progenitor rubble pile. For the cases with an elongated body, we tested 30 different encounters because of the substantial changes in outcome depending on the alignment of the body’s long axis at perihelion. Disruption is more likely if the spin angular momentum is aligned with the encounter angular momentum (Richardson et al. 1998), though as the spin rate decreases this becomes less important. Elongation is less important in the non-spinning case and so only spherical bodies were tested. No cases of retrograde rotators were tested as they are less likely to disrupt than non-spinning cases (Richardson et al. 1998), and the results below show non-spinning as a very unlikely disruption scenario.

The results of these simulations are presented in Figure 1, which shows the fraction, \( f \), of simulations in which mass loss exceeded 2%, 50%, and 80% of the total mass of the progenitor for each of the tested bulk density values. A conservative estimate of survival is given by \( 1 - f_{30\%} \), while \( f_{10\%} \) depicts catastrophic disruptions. For bodies with initially no rotation, there is a sharp increase in the degree of the disruption as seen by the increasing \( f \) for densities \(<0.15 \text{ g cm}^{-3}\). The disruptions begin at higher densities for the bodies with prograde rotation, with disruptions beginning at 0.3 g cm\(^{-3}\) in the spherical case. Elongated bodies with prograde rotation, the extreme case tested, experience mass loss even earlier, with some bodies at densities up to 0.7 g cm\(^{-3}\) disrupting. The cases with elongation had nearly bi-modal results, with either no mass-loss or dramatic mass loss due to the importance of the long-axis location at perihelion (Richardson et al. 1998). Disruption did not occur in any simulations in which the density was >0.7 g cm\(^{-3}\).

3. DISCUSSION

The first three columns of Table 1 give the nuclear parameters that affect survival, their considered ranges, and a qualitative description of their effect on survivability. We specifically tested a range of density, axis ratio, and sense of rotation. The simulations are scale invariant, and thus can be translated to any pre-encounter nuclear size, so in effect radius has also been

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4 http://www.astro.umd.edu/~ma/evap/index.shtml
Table 1
Factors Affecting ISON’s Survivability

| Parameter          | Value(s) | Qualitative Description of Results | Likely Value\(^a\) |
|--------------------|----------|------------------------------------|--------------------|
| Radius (km)        | <0.2     | Does not survive due to mass loss from sublimation | 0.4–2.0            |
|                    | 0.2–1.0  | Survival dependent on combination of other factors; more likely to survive the larger the radius |                   |
|                    | >1.0     | Survives for most scenarios if density >0.1 g cm\(^{-3}\) |                   |
| Density (g cm\(^{-3}\)) | <0.1     | Does not survive for most scenarios | 0.4–0.7            |
|                    | 0.1–0.7  | Survival dependent on combination of other factors; more likely to survive the higher the density |                   |
|                    | >0.7     | Survives for most scenarios |                   |
| Axis ratio (\(a:b\)) | 1.0      | Survival dependent on combination of other factors; more likely to survive the smaller the ratio \(a:b\) | 1.0–2.6            |
| Sense of rotation  | Prograde | Survival dependent on combination of other factors | Retrograde         |
|                    | Retrograde | Survival for most scenarios |                   |
|                    | No spin  | Survival dependent on combination of other factors; more likely to survive than prograde case; less likely to survive than retrograde case |                   |
| Rotation period (hr) | >\(P_{\text{crit, 50\%}}\) | Survival dependent on combination of other factors; more likely to survive the longer the rotation period | 4–180+            |
|                    | \(P_{\text{crit, 50\%}}\) | Survival dependent on combination of other factors |                   |
|                    | <\(P_{\text{crit, 50\%}}\) | Survival dependent on combination of other factors |                   |

Note.\(^4\) See the text for the sources of these values.

Figure 1. Fraction of simulations with mass loss exceeding 2% (top), 50% (middle), and 80% (bottom) as a function of density. Three cases are plotted: non-spinning spherical nucleus (red squares), prograde spherical nucleus (blue circles), and prograde elongated nucleus (black triangles). No retrograde cases were plotted because mass loss is less likely than for the non-spinning case and therefore only occurs for extremely low densities (<0.1 g cm\(^{-3}\)). The vertical dashed line shows the density at which Sridhar & Tremaine (1992) predict ISON should begin to shed mass.

(A color version of this figure is available in the online journal.)

sampled (noting that the largest remnant needs to be \(\geq 0.2\) km to survive the remainder of the apparition). Therefore, the only parameter not specifically tested is rotation period, which has a well understood degeneracy with density (Asphaug & Benz 1996; Richardson et al. 1998). Rotation periods potentially span a tremendous range that, if fully explored, would have been too CPU-intensive for the current Letter. The effect of rotation period can, however, be visualized in Figure 1 by shifting the curves up and to the right for shorter prograde rotation periods (mass loss due to tidal forces results at larger densities) or down and to the left for longer prograde, or any retrograde, rotation periods (mass loss due to tidal forces only occurs at very low densities).

The last column in Table 1 gives the likely range of values for each parameter for ISON. While radius (discussed in Section 1.3) and sense of rotation (retrograde; provided by T. Farnham based on the pole orientation from Li et al. 2013) are partially constrained by published observations, the rest are not. Comet nuclear properties are notoriously difficult to measure, and the properties of dynamically new comets like ISON are almost completely unconstrained. Therefore, the ranges of the remaining parameters cover the known values of all comets as compiled from Lamy et al. (2004), Samarasinha et al. (2004), Weissman et al. (2004), A’Hearn (2011), and our own literature search for more recent publications.

ISON appears likely to survive the combination of mass loss due to sublimation and tidal disruption for most plausible scenarios. If it is “typical”—radius \(\sim 1\) km, density \(\sim 0.5\) g cm\(^{-3}\), axis ratio \(\sim 1\), rotation period \(\sim 24\) hr, and a random sense of rotation (or retrograde as the preliminary results suggest)—it is very likely to survive the encounter. Given that comet densities are relatively well constrained to be near \(\sim 0.5\) g cm\(^{-3}\), the rotation period is the parameter whose plausible range poses the largest threat to ISON’s ability to survive perihelion. For a density of \(\sim 0.5\) g cm\(^{-3}\), ISON would lose mass for many scenarios in which the rotation period was prograde and faster...
than \(~9\) hr, with tidally driven mass loss increasing as rotation period decreases. Roughly 30\% of measured comet rotation periods are \(<9\) hr, although this is likely overestimated because shorter rotation periods are easier to measure. Furthermore, assuming that sense of rotation is random, half of these fast rotators would be retrograde and therefore unlikely to disrupt.

As of 2013 August, none of the parameters in our simulations have been tightly constrained for ISON, although some (most likely rotation period or pole orientation) may yet be determined prior to perihelion. However, even if these quantities are constrained, Samarasinha & Mueller (2013) showed that ISON’s rotation is likely to be highly excited near perihelion so values determined at larger heliocentric distances may not hold through perihelion, and mass loss due to spin-up may occur. Further investigations of this possibility are beyond the scope of this Letter. Also beyond the scope are the effects of sublimation driven mass loss during the encounter, although we do not expect it to alter our results substantially.

We hope that observations around and after perihelion may yield enough information to infer many of these parameters and therefore conclusively determine ISON’s susceptibility (or lack thereof) to tidal disruption. Furthermore, the current work should serve as a guide for studies after perihelion to estimate ISON’s density based on measurable quantities and the results of the perihelion passage.

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