THE SIZE AND FRAGMENTATION OF THE NUCLEUS OF COMET C/2012 S1 (ISON). J. K. Steckloff[1], J. Keane[2], M. M. Knight[3], J. Kleyna[2], S. N. Milam[4], I. Coulson[5], and K. Meech[2], S. A. Jacobson[6], H. J. Melosh[1,7], [1]Department of Physics and Astronomy, Purdue University, 525 Northwestern Avenue, West Lafayette IN 47907 (jstecklo@purdue.edu), [2]Institute for Astronomy, University of Hawaii, Honolulu, HI 96822, [3]Lowell Observatory, Flagstaff, AZ 86001, [4]NASA Goddard Space Flight Center, Greenbelt, MD 20771, [5]Joint Astronomy Centre, Hilo, HI 96720, [6]Observatoire de la Côte d'Azur, 06460 Saint-Vallier-de-Thiey, France, [7]Department of Earth, Atmospheric, and Planetary Sciences, Purdue University, West Lafayette IN 47907

Introduction: Dynamically new comet C/2012 S1 (ISON) was discovered more than a full year before its perihelion passage on 28 November 2013. This advanced notice allowed for a massive observation campaign to be organized using resources located throughout the inner Solar System. While no instrument was able to resolve the nucleus of Comet ISON, observers employed various techniques to estimate the size of the nucleus from observations made by the Mars Reconnaissance Orbiter's HiRISE instrument [1], Hubble Space Telescope (HST) [2], Solar and Heliospheric Observatory's Solar Wind Anisotropies instrument (SOHO-SWAN) [3], and the James Clerk Maxwell Telescope's (JCMT) SCUBA-2 instrument [4]. These size estimates span Comet ISON's sunward path from near the orbit of Mars to shortly before perihelion. This data set allows us to study how volatile ice sublimation affected Comet ISON's nucleus and investigate the causes of outbursts and fragmentations that ultimately doomed Comet ISON.

Size of ISON's Nucleus: In Figure 1 we plotted the published estimates of the effective radius of Comet ISON's nucleus (or nucleus fragments) of <625 m at a heliocentric distance of 360 Solar Radii ($R_\odot$), where 1 $R_\odot$ is equivalent to 0.00465 AU [1]; 680±20 m at 320 $R_\odot$ [2]; 350-1250 m at 253 $R_\odot$ [3]; and 108^{+81}_{-32} m, 19^{+6}_{-4} m, $1.8^{+0.7}_{-0.4}$ m (error from one pixel uncertainty in position) at 103, 38, and 23 $R_\odot$ respectively [4]. We additionally denoted the heliocentric locations of three distinct events in Comet ISON's history: two that are suspected fragmentation events at heliocentric distances of 36 and 88 $R_\odot$ [5], and an additional outburst event at ~140 $R_\odot$ (referred to in [6] and hereafter as "Event 1") that could be due to fragmentation of the nucleus [3,6].

Evolution of nucleus. We modeled the size evolution of the nucleus using the mass loss rates observed by SOHO-SWAN, which observed Comet ISON between 24 October and 23 November 2013 [3]. We used the deconvolved daily average water production rates from the SOHO-SWAN observations and reasonable assumptions on the composition and density of the nucleus [3] to allow the end-member effective radius constraints of Comet ISON's nucleus to evolve over the period of observations. Fortuitously, the SOHO-SWAN observations span both Event 1 and an estimate of the size of the nucleus (or nucleus fragments) at 102 $R_\odot$ in [4], allowing us to investigate the nature of this event.

Nucleus Fragmentation: We compare the sizes of the nucleus before and after each suspected fragmentation event, and investigate the nature of the fragmentation using the number of fragments created.

Event 1. We apply the observed deconvolved daily average water production rates from the SOHO-SWAN observations to the end-member size constraints of 350-1250 m [3] to allow them to lose mass and change their effective radii over time. We allow this mass loss to evolve the end-members to 103 $R_\odot$, and compare this result with the effective nucleus radius of 108^{+81}_{-32} m at 103 $R_\odot$ [4]. Since the lower bound of this evolved size range is more than 100m larger than the upper error bar of the size estimate, sublimation-driven mass loss alone cannot explain the size evolution. We therefore conclude that Event 1 is likely a fragmentation event.

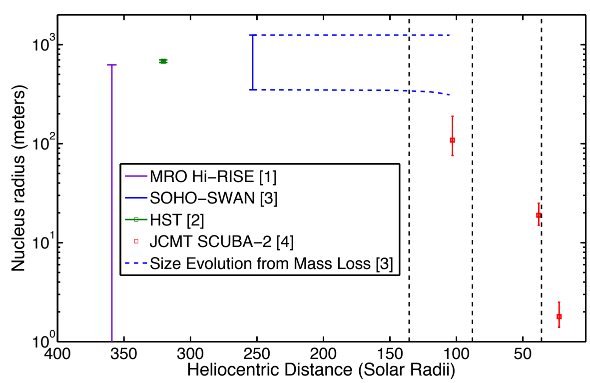

Figure 1: A plot of the size estimates of Comet ISON as a function of heliocentric distance, along with the locations of three suspected nucleus fragmentation events (denoted by the vertical dotted lines). Comet ISON's perihelion position (2.7 $R_\odot$) is located at the right side of the plot.

We next consider the mechanism of the fragmentation. It had been suggested that sublimative torques could increase the rotation rate of Comet ISON to the point of fission [7]. However two lines of evidence agrue against rotational fragmentation. First, the rotational period of Comet ISON's nucleus was estimated to be ~10.4 hours at 320 $R_\odot$ [2]. In order for the nucleus to become tensile (and thus allow for rotational fission), the rotation period would have to decrease to ~2.2 hours [8], which is highly unlikely even for a very active comet in the 45 days between the observation of ISON's rotation period and Event 1 [7]. Second, rotational fragmentation should occur at seemingly random heliocentric distances (to first order). However comet C/1996 B2 (Hyakutake) also experienced an outbursting event at the same heliocentric distance [3,9], suggesting instead that this is the location of a specific and enigmatic event that affects some comet nuclei.

Fragmentation at 88 $R_\odot$. We next turn our attention to the suspected fragmentation event at 88 $R_\odot$. Since mass loss has a greater effect on smaller fragments nearer to the Sun, we again model the size evolution of the 108^{+81}_{-32} m fragments at 103 $R_\odot$ [4] as they approached 38 $R_\odot$, where the fagements are estimated to be 19^{+6}_{-4} m in radius [4]. Since the observed mass loss rates do not span this region of space [3], we instead directly model sublimation-driven surface erosion.

In addition to primary volatile sublimation (directly from the nucleus), we also consider the effects of secondary sublimation (from icy grains in the coma, previous ejedted from the nucleus), which can greatly enhance the rate of sublimation-driven surface erosion. We estimate the effects of secondary sublimation by comparing the surface area of the nucleus obtained from modeling the optical contribution of the nucleus to the HST observations of Comet ISON in [2] to the minimum surface area needed to account for the observed water production rates in [3], which reveals that only ~30% of the water production is due to primary sublimation. Thus, secondary sublimation of water from icy grains, which originate from the nucleus, is likely increasing the rate of sublimative erosion by a factor of ~3.4. If we assume that this factor holds for all heliocentric distances, primary and secondary sublimation together would erode the top ~20 m of the surface between heliocentric distances of 103 and 38 $R_\odot$. However, this is still at least half an order of magnitude too slow to alone account for the drop in the size of the nucleus fragments to 19^{+6}_{-4} m over this interval. Thus, the fragments of Comet ISON's nucleus likely fragmented further at 88 $R_\odot$.

Fragmentation at 36 $R_\odot$. Lastly, we apply the same analysis to the suspected fragmentation event at 36 $R_\odot$. Between 38 and 23 $R_\odot$ (where the nucleus fragments are estimated to be $1.8^{+0.7}_{-0.4}$ m in radius), erosion from primary and secondary sublimation would remove the top ~15 m from the fragments. From this consideration, sublimation-driven mass loss alone could possibly explain the observed decrease in fragment sizes. However, since the overlap in error bars is not large, a fragmentation event could also plausibly explain the observed fragment size change. However, mass loss would not explain the drastic increase in brightness of Comet ISON at 36 $R_\odot$ [5], which would suggest that the fragmentation interpretation of the event at 36 $R_\odot$ is more plausible.

Comet ISON and Comet 67P: ISON's final, ~2 m radius fragments are suggestive of a structural link with the Rosetta Spacecraft's target, Comet 67P/Churyumov-Gerasimenko. The OSIRIS instrument onboard Rosetta returned very high resolution images of the nucleus of Comet Churyumov-Gerasimenko, revealing that the comet appears to be constructed out of meter-scale "dinosaur egg"-shaped pieces [10], consistent with the last size estimate of Comet ISON's fragments at 23 $R_\odot$. While this similarity in sizes does not entail that these fragments are necessarily the same as the "dinosaur eggs" of Comet Churyumov-Gerasimenko, they are suggestive of a fundamental link between the formational mechanism of these two comets. If this proves to be the case, this link would further suggest that at least some Oort Cloud Comets and JFCs formed under similar conditions.

Conclusions: We have shown that Comet ISON likely underwent a crumbling fragmentation at heliocentric distances of ~140 $R_\odot$. We have likewise confirmed that additional crumbling fragmentation events likely occurred at 88 $R_\odot$ and 36 $R_\odot$, although the evidence for the latter is more ambiguous. Furthermore, the final size of ISON's fragments is similar to the meter-scale "dinosaur egg" pieces observed on Comet 67P, hinting at a link between these two comets.

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