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UNUSUAL WATER PRODUCTION ACTIVITY OF COMET C/2012 S1 (ISON): OUTBURSTS AND CONTINUOUS FRAGMENTATION

M. R. COMBI¹, N. FOUGERE¹, J. T. T. MÄKINEN², J.-L. BERTAUX³, E. QUÉMERAIS³, AND S. FERRON⁴

¹ Department of Atmospheric, Oceanic, and Space Sciences, University of Michigan,
2455 Hayward Street, Ann Arbor, MI 48109-2143, USA; mcombi@umich.edu

² Finnish Meteorological Institute, Box 503, SF-00101 Helsinki, Finland

³ LATMOS/IPSL, Université de Versailles Saint-Quentin, 11, Boulevard d'Alembert, F-78280 Guyancourt, France

⁴ ACRI-st, Sophia-Antipolis, France

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ABSTRACT

The Solar Wind ANisotropies (SWAN) all-sky hydrogen Ly α camera on the *Solar and Heliospheric Observer* (*SOHO*) satellite observed the hydrogen coma of comet C/2012 S1 (ISON) for most of the last month of its activity from 2013 October 24 to November 24, ending just 4 days before perihelion and its final disruption. The water production rate of the comet was determined from these observations. *SOHO* has been operating in a halo orbit around the Earth–Sun L1 Lagrange point since its launch in late 1995. Most water vapor produced by comets is ultimately photodissociated into two H atoms and one O atom producing a huge hydrogen coma that is routinely observed in the daily SWAN images in comets of sufficient brightness. Water production rates were calculated from 22 images over most of the last month of the pre-perihelion apparition. The water production rate increased very slowly on average from October 24.9 until November 12.9, staying between 1.8 and $3.4 \times 10^{28} \text{ s}^{-1}$, after which it increased dramatically, reaching 1.6 to $2 \times 10^{30} \text{ s}^{-1}$ from November 21.6 to 23.6. It was not detected after perihelion on December 3.7 when it should have been visible. We examine the active surface area necessary to explain the water production rate and its variation and are able to place constraints on the physical size of the original nucleus necessary to account for the large amount of activity from November 12.9 and until just before perihelion.

Key words: comets: general – comets: individual (C/2012 S1 (ISON)) – Oort Cloud – ultraviolet: general

1. INTRODUCTION

Comet C/2012 S1 (ISON) was discovered on 2012 September 21 by Nevski and Novichonok of the International Scientific Optical Network (ISON) in Kislovodsk, Russia, as part of their normal near-Earth object search program (see Nevski et al. 2012). A search for prediscovery images and subsequent refinement of its orbit showed that it would reach a perihelion distance of 0.0124 AU (~ 2.7 solar radii from the center of the Sun) on 2013 November 28. Its eccentricity of 0.9999946 indicated that it was a true Oort Cloud comet on its first trip into the inner solar system since it was formed ~ 4.5 Gyr ago.

A number of early observations of comet ISON obtained before 2013 June have been reported (Knight & Walsh 2013; Li et al. 2013; Meech et al. 2013; O'Rourke et al. 2013). Many observations were reported publicly and informally on Web sites and a few have been reported in IAU Circulars and the Central Bureau of Electronic Telegrams.

O'Rourke et al. (2013) presented a marginal detection of CO with a production rate of $\sim 3\text{--}4.5 \times 10^{27} \text{ s}^{-1}$ from 2013 mid-March to early April (4.18–4.45 AU) and observations of the dust coma and activity levels. Meech et al. (2013) reported photometric observations from right after discovery (6.28 AU) until 2013 June when it reached solar conjunction. They reported a search for CO and HCN from March (4.52 AU) until mid-June (3.35 AU) and found an upper limit for CO of $\sim 4 \times 10^{27} \text{ s}^{-1}$. They also report water production rates of $3 \times 10^{26} \text{ s}^{-1}$ at 4.57 AU and $6 \times 10^{26} \text{ s}^{-1}$ at 3.86 AU as well as several upper limits.

Early observations of the dust coma by Li et al. (2013) found the nucleus had a nearly constant illumination combined with high obliquity. They predicted that in the 1–2 weeks around

perihelion a significant fraction of the surface that had not been exposed to sunlight would be exposed for the first time a possible change in volatile composition and/or triggering large outbursts. Knight & Walsh (2013) examined a number of factors, some known and some unknown, before 2013 August that might give indicators as to whether C/2012 S1 (ISON) would survive perihelion.

The *Solar and Heliospheric Observatory* spacecraft (*SOHO*) has been in a halo orbit around the L1 Lagrange point about 1 million km sunward of the Earth since shortly after its launch in December of 1995. While the original purpose of the Solar Wind ANisotropies (SWAN) instrument on board *SOHO* is to study the properties of the solar wind through its ionization of neutral hydrogen from the interplanetary medium, SWAN has proved to be an important monitor of cometary water production rates providing observations of the hydrogen Ly α comae of many new, long-period and Jupiter family comets for over 18 yr (Bertaux et al. 1997, 2014; Combi et al. 2000, 2005, 2008, 2011a; Mäkinen et al. 2001a, 2007).

Based on some early projections of activity, we had hoped to obtain useful images of the hydrogen Ly α coma with the SWAN instrument on the *SOHO* spacecraft once the comet achieved a sufficiently large solar elongation angle in late August 2013. However, a flattening out of the activity throughout most of 2013 precluded this, and the first detection with SWAN came on 2013 October 24.

Here we present large field-of-view (FOV) ultraviolet observations of the hydrogen Ly α coma of C/2012 S1 (ISON) made with the SWAN instrument on the *SOHO* spacecraft (Bertaux et al. 1997). An analysis of these observations yields total water production rates covering most of the month of the comet's apparition before perihelion when it appeared to be completely

disrupted. In addition to calculating water production rates from each image, we used our time-resolved model (Mäkinen & Combi 2005) to calculate daily average values of the water production from the nucleus and nearby regions in order to specify the times of abrupt changes in water production, which are normally not seen instantly in the hydrogen coma observed by the large SWAN FOV. We also calculate the active surface areas of water ice necessary to explain the water production rate values and analyze those results to study the disruption and fragmentation of the nucleus and with the final two weeks of water production rate activity obtain an estimate of the size of the nucleus before disintegration.

2. OBSERVATIONS AND BASIC MODEL ANALYSIS

C/2012 S1 ISON was observed in 22 full-sky SWAN images from 2013 October 24 through November 23. Beginning on November 24 the comet entered SWAN's solar avoidance area. The outer part of the hydrogen coma could be seen just outside the avoidance area with a brightness similar to that on November 23. After perihelion, when the comet should have appeared outside of the solar avoidance area on December 3, the hydrogen coma was not detectable.

The SWAN Ly α imager makes daily images of the full-sky with $1^\circ \times 1^\circ$ resolution enabling nearly continuous coverage of comets brighter than visual magnitude 10 or 11. With its position at L1 comets can be observed at solar elongation angles as small as 15° and there is no limitation regarding the north/south location of the comet or the usual limitations plaguing ground-based or Low-Earth-Orbit-(LEO-) based spacecraft observations. The SWAN instrument, its detectors, observing procedures and sensitivity have been described by Bertaux et al. (1997), and the recent update to the SWAN calibration has been described by Combi et al. (2011b).

Most water molecules in comets are photodissociated into two hydrogen atoms and one oxygen atom. A series of detailed studies of both images and high resolution spectra of hydrogen comae have enabled us to develop a reliable set of models to determine water production rates from SWAN images of comets. These are explained in detail in two papers (Mäkinen & Combi 2005; Combi et al. 2005).

We were able to use both modes of our time-resolved model (TRM) to calculate water production rates. The single-image water production rates are calculated from each image at the time of the observation using our model that accounts for the photochemical lifetimes, their heliocentric distance dependence, exothermic kinetics and partial thermalization of hot H atoms. We were also able to use our processing mode that analyzes sequences of images simultaneously in order to extract daily average values of the water production rate of the nucleus and region around the nucleus using the temporal information present in the images enabled by the long lifetime of H atoms and the large SWAN FOV. This temporal deconvolution process can extract daily average values of the initial water production in the vicinity of the nucleus (including surrounding icy fragments) accounting for the photodissociation lifetimes of H₂O and OH and the transport times and lifetimes of the hydrogen atoms throughout the large SWAN FOV. Depending on the observer-comet distance, transient features in water production typically take 1–3 days to make themselves visible in the extended H coma.

The fluorescence rate or g -factor was calculated from the composite solar Ly α data taken from the University of

Table 1
SOHO/SWAN Observations of Comet 2012 S1 (ISON)
and Water Production Rates

| Date (2013 UT) | r (AU) | Δ (AU) | g (s ⁻¹) | Q (10 ²⁸ s ⁻¹) | δQ (10 ²⁸ s ⁻¹) |
|-------------------|-------------|------------------|---------------------------|--|---|
| Oct 24.9 | 1.163 | 1.421 | 0.002295 | 1.52 | 0.53 |
| Oct 25.9 | 1.140 | 1.391 | 0.002287 | 2.79 | 0.20 |
| Oct 28.9 | 1.071 | 1.304 | 0.002274 | 1.93 | 0.40 |
| Oct 29.9 | 1.048 | 1.275 | 0.002288 | 1.64 | 0.73 |
| Oct 30.9 | 1.024 | 1.247 | 0.002298 | 2.26 | 0.36 |
| Oct 31.9 | 1.000 | 1.219 | 0.002372 | 2.17 | 0.51 |
| Nov 1.9 | 0.975 | 1.191 | 0.002365 | 1.99 | 0.32 |
| Nov 3.9 | 0.926 | 1.137 | 0.002424 | 2.25 | 0.20 |
| Nov 5.9 | 0.875 | 1.085 | 0.002391 | 1.79 | 0.35 |
| Nov 6.9 | 0.849 | 1.060 | 0.002380 | 1.75 | 0.39 |
| Nov 8.9 | 0.796 | 1.012 | 0.002334 | 3.39 | 0.19 |
| Nov 9.9 | 0.768 | 0.989 | 0.002398 | 3.20 | 0.25 |
| Nov 10.9 | 0.741 | 0.968 | 0.002379 | 3.42 | 0.22 |
| Nov 11.9 | 0.712 | 0.948 | 0.002439 | 2.69 | 0.31 |
| Nov 12.9 | 0.683 | 0.928 | 0.002481 | 2.49 | 0.30 |
| Nov 13.9 | 0.654 | 0.911 | 0.002577 | 5.25 | 0.16 |
| Nov 14.9 | 0.624 | 0.895 | 0.002496 | 11.93 | 0.08 |
| Nov 16.6 | 0.570 | 0.871 | 0.002434 | 35.00 | 0.05 |
| Nov 19.6 | 0.470 | 0.846 | 0.002243 | 38.46 | 0.08 |
| Nov 21.6 | 0.397 | 0.842 | 0.002060 | 193.60 | 0.05 |
| Nov 22.6 | 0.358 | 0.845 | 0.001953 | 153.80 | 0.08 |
| Nov 23.6 | 0.316 | 0.852 | 0.001809 | 233.70 | 6.10 |

Notes. Date (UT) in 2013; r : heliocentric distance (AU); Δ : geocentric distance (AU); g : solar Ly α g -factor (photons s⁻¹) at 1 AU; Q : water production rates for each image (s⁻¹); δQ : internal 1σ uncertainties.

Colorado LASP Web site⁵. The heliocentric velocity dependence of the g -factor was calculated from the solar Ly α line profile (Lemaire et al. 1998). The calibration of SWAN at Ly α was revised in 2011 (Combi et al. 2011b) from previous measurements by Quémerais et al. (2009) and Clarke et al. (1998).

Figures 1(a) and (b) show a sample of a SWAN comet image and the model analysis procedure. Figure 1(a) shows the FOV around the comet from the full-sky image of 2013 November 11. The FOV is a 30° square centered on the comet with the Sun's direction to the right. The missing pixels on the right of the image are part of the solar avoidance area. The red-line cut centered on the comet corresponds to the profile shown in Figure 1(b). The red profile in Figure 1(b) corresponds to the data; the green profile is the model fit to the coma; the blue straight line along the bottom is the model fit to the interplanetary Ly α background of brightness ~ 650 Rayleighs.

The observational circumstances, g -factors, water production rates calculated from the individual SWAN images of C/2012 S1 (ISON), and their formal statistical 1σ uncertainties are given in Table 1. A preliminary version of the single-image production rates was released by Combi et al. (2013) using an estimate of the H Ly α g -factors because the final versions from the LASP web site were not available for the entire data set at that time. The new results are similar but not identical, varying by up to several percent. The TRM analysis, by analyzing entire sequences of images, provides daily average values of the water production rate from the nucleus and its immediate vicinity. These are given in Table 2 with 1σ statistical uncertainties.

The results of both sets of water production rates are plotted as a function of time in Figure 1(c). The points show the production rates from the single images. The histogram gives

⁵ <http://lasp.colorado.edu/lisird/lya/>

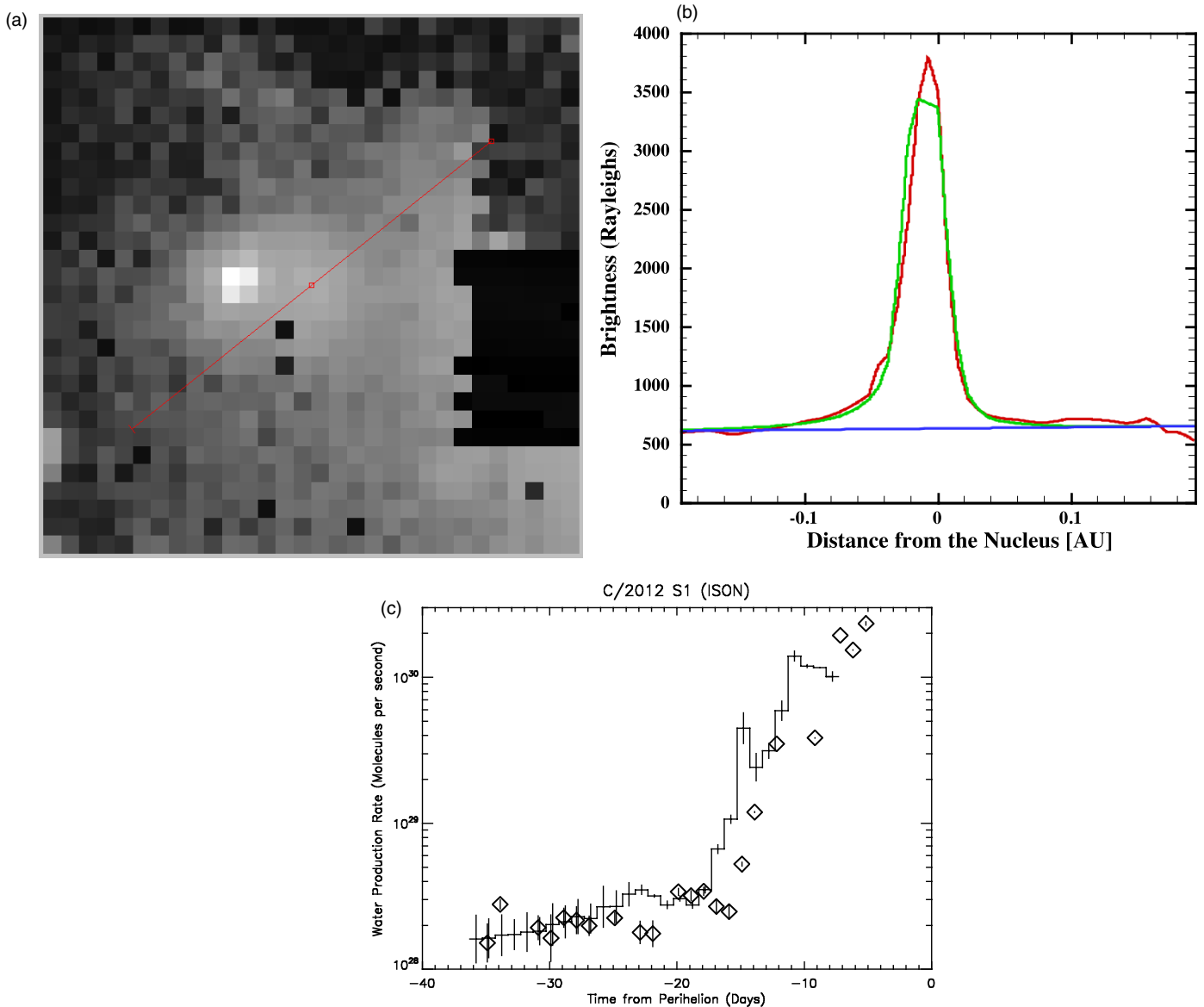


Figure 1. (a) SWAN image of comet C/2012 S1 (ISON) (top left) on 2013 November 11.9. (b) A brightness profile of the coma and interplanetary background (top right) corresponds to the red line cut in image (a). The image in (a) is centered on the comet, where the bright spot to the left of center is a bright field star. In (b) the red profile gives the observed coma, the green profile gives the model fit to the coma, and the blue straight line along the bottom gives the model fit to the interplanetary background. (c) Water production rate of Comet 2012 S1 (ISON) plotted as a function of time in days from perihelion on 2013 November 28.780. The diamonds give the values calculated from each single image. The histogram gives the daily average water production rate from the region of the nucleus computed with the time-resolved model. The single-image values smear and delay rapid changes in the water production rate for ~ 3 days because of the filling time of the hydrogen coma in the large SWAN FOV. The error bars correspond to internal 1σ uncertainties from photon counts and background subtraction. Systematic uncertainties from model assumptions and calibration are of the order of 30% as have discussed previously (Mäkinen et al. 2001b; Combi et al. 2005).

the daily average water production rates from the deconvolution process. The uncertainties are somewhat larger for the daily average values. As expected, abrupt changes to the water production are ~ 3 days earlier in the daily average values than in the single-image values. This results from the slower response time of H atoms which are both daughter and granddaughter photodissociation products of water and which take time to propagate out to fill the H coma seen in the large SWAN FOV. The beginning of the rapid rise seen between the images recorded on November 12.9 and 13.9 is due to the rise of water production increase from the nucleus and its immediate environs beginning ~ 3 days earlier as seen in the deconvolved daily average values. The daily average water production rates also show a distinct outburst peak 15 days before perihelion on November 12, again two days before it is seen in the single-image values.

Overall, the water production rate increased by about two orders of magnitude (from $2.5 \times 10^{28} \text{ s}^{-1}$ to $2.3 \times 10^{30} \text{ s}^{-1}$) from mid-November to the last observations a few days before perihelion.

3. DISCUSSION

The active surface area of the comet, which includes the nucleus and the surfaces of any surrounding icy grain halo or fragments that might have been released from the nucleus, can be calculated from the water production rate using the method of Cowan & A'Hearn (1979) for an assumed rapidly rotating sphere (or spheres in the case of fragments). A plot of the active surface area as a function of time for the single-image and deconvolved daily average production rates is shown in Figure 2.

Table 2

Deconvolved Daily Average Water Production Rate of Comet 2012 S1 (ISON)

| T (days) | r (AU) | Δ (AU) | Q (10^{28} s^{-1}) | δQ (10^{28} s^{-1}) |
|---------------|-------------|------------------|-------------------------------------|--|
| -35.78 | 1.182 | 1.459 | 1.61 | 0.73 |
| -34.78 | 1.160 | 1.430 | 1.63 | 0.59 |
| -33.78 | 1.137 | 1.400 | 1.71 | 0.65 |
| -32.78 | 1.115 | 1.371 | 1.73 | 0.46 |
| -31.78 | 1.092 | 1.342 | 1.80 | 0.64 |
| -30.78 | 1.068 | 1.313 | 1.82 | 0.43 |
| -29.78 | 1.045 | 1.284 | 2.03 | 0.79 |
| -28.78 | 1.021 | 1.256 | 2.11 | 0.60 |
| -27.78 | 0.997 | 1.228 | 2.30 | 0.71 |
| -26.78 | 0.973 | 1.200 | 2.23 | 0.57 |
| -25.78 | 0.948 | 1.173 | 2.68 | 1.02 |
| -24.78 | 0.923 | 1.146 | 2.69 | 0.76 |
| -23.78 | 0.898 | 1.120 | 3.27 | 0.66 |
| -22.78 | 0.872 | 1.094 | 3.50 | 0.27 |
| -21.78 | 0.846 | 1.069 | 3.18 | 0.06 |
| -20.78 | 0.819 | 1.044 | 2.76 | 0.16 |
| -19.78 | 0.792 | 1.021 | 3.05 | 0.12 |
| -18.78 | 0.765 | 0.998 | 2.76 | 0.15 |
| -17.78 | 0.737 | 0.977 | 3.51 | 0.18 |
| -16.78 | 0.709 | 0.956 | 6.67 | 0.47 |
| -15.78 | 0.680 | 0.937 | 10.66 | 0.69 |
| -14.78 | 0.650 | 0.919 | 44.86 | 12.21 |
| -13.78 | 0.620 | 0.903 | 24.20 | 5.87 |
| -12.78 | 0.589 | 0.888 | 31.34 | 3.94 |
| -11.78 | 0.557 | 0.876 | 59.17 | 9.71 |
| -10.78 | 0.525 | 0.865 | 139.70 | 11.42 |
| -9.78 | 0.491 | 0.857 | 119.20 | 2.75 |
| -8.78 | 0.456 | 0.852 | 116.70 | 0.50 |
| -7.78 | 0.420 | 0.849 | 101.10 | 7.80 |

Notes. ΔT : Time from perihelion on 2013 November 28.780 UT in days; r : heliocentric distance (AU); g : geocentric distance (AU); g : solar Ly α g -factor (photons s^{-1}) at 1 AU; Q : daily average water production rates (s^{-1}) from the TRM; δQ : internal 1σ uncertainties.

The active surface from the daily average production rates accounts for the actual water production from the nucleus and its immediate vicinity and is more indicative of the actual production of water from the comet as a whole. Just like the production rate comparison, the active area as calculated from the daily average results leads that calculated from the single-images by ~ 3 days throughout the time period. This makes sense in terms of the time it takes to see a change in the water production rate reflected in the whole H coma seen in the SWAN FOV. The active surface area is generally flat starting at about 7 km^2 just before the first day of observation, October 23, and continuing to November 6. It then decreases over the next four days reaching a low value of about 4 km^2 on November 9. Assuming a 100% water sphere this would correspond to a nucleus radius of between 0.56 and 0.75 km. After this date the active surface area increases dramatically by more than a factor 25 to its peak value on November 18 of just over 100 km^2 .

While it is clear that the nucleus is not spherical, the active area at least provides an estimate of the total active surface area. Also while the calculation used assumes a rapid rotator, it is only for heliocentric distances larger than for these observations where there is a significant difference among rotation models (Cowan & A'Hearn 1979). It is unlikely that fragments released from the nucleus will have zero rotation. In order to model the detailed sublimation of a released swarm of fragments would require a more involved approach (e.g., Fougere et al. 2012,

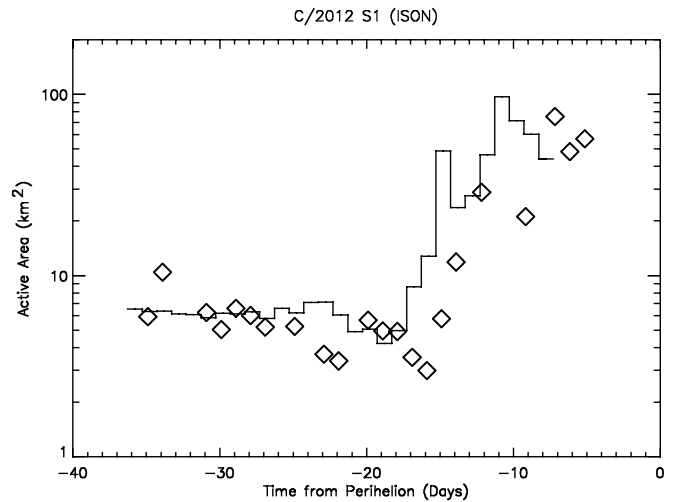


Figure 2. Active surface area (km^2) of comet C/2012 S1 (ISON) as a function of time from perihelion in days. The diamonds give the calculated active surface area from the single-image values for a water dominated surface required to produce the water production rate. The histogram gives the calculated active surface area from the daily average values determined with the time-resolved model. The method of Cowan & A'Hearn (1979) for a rapid rotator with a Bond albedo of 0.05 and a perfect thermal emissivity was used.

2013) that cannot be constrained by these data alone and is beyond the scope of this paper.

From early *HST* measurements (Kelley et al. 2014) a generous upper limit estimate of the maximum radius of the nucleus was 2 km. Another estimate from the HIRISE camera on the Mars Reconnaissance Orbiter spacecraft (Milkovich et al. 2013) was ~ 1 km. Therefore, it is possible that the activity from mid-October until mid-November was due to water sublimation mostly from a small highly active comet nucleus. After November 9 the active surface area required to supply the observed water production was too large to have been produced by a small nucleus of 1–2 km radius. Given the observed factor of two single-day outburst seen on November 12, it is quite clear that this last period was dominated by the rapid shedding of fragments by the nucleus itself, until some time just before perihelion when it was completely spent. This outburst, which is only clear in the daily average data, corresponds exactly to Event 1 in the substantial analysis of the entire apparition by Sekanina & Kracht (2014).

This single-day outburst on November 12 is similar in duration to and heliocentric distance to one of the three outbursts reported by Combi et al. (2005) in comet 1996 B2 (Hyakutake). This large outburst of nucleus fragments appears to have been released in an abrupt event on top of the continuous release of sublimating nucleus fragments that began on November 9 with the large increase in overall production rate. There is also evidence for a smaller but more extended outburst earlier on November 5 lasting about 3.5 days. The three outbursts in Hyakutake showed a consistent trend of decreasing duration with decreasing heliocentric distance, indicating shorter lifetimes of the released fragments with the increased solar heating. The two outbursts seen in 2012 S1 (ISON) follow a very similar trend. Further evidence for the release of fragments in 2012 S1 (ISON) was also found in the observations of wing features in the coma throughout this period on November 14, 16, and 18 (Boehnhardt et al. 2013). This is also reminiscent of the gaseous species wings in the coma of 1996 B2 (Hyakutake) associated with the interactions of the gas flows among the nucleus and the fragments (Harris et al. 1997).

Table 3
Estimates of a Spherical Nucleus Radius for C/2012 S1 (ISON)

| Water mass fraction of the nucleus | $f = 1$ | $f = 1/2$ | $f = 1/3$ |
|--|----------------------|----------------------|----------------------|
| Total mass lost from Day -35.78 to Perihelion (kg) | 3.6×10^{10} | 7.2×10^{10} | 1.1×10^{11} |
| Radius of spherical nucleus from total mass loss (m) | 280 | 350 | 400 |
| Active area on Day $= -35.78$ (km ²) | 6.55 | 13.1 | 19.6 |
| Radius of spherical nucleus from active area on Day $= -35.78$ (m) | 720 | 1020 | 1250 |

Both the level of water production rate before November 9 as well as the total water production throughout the apparition can be used to provide estimates of the total mass and size of the nucleus. Assuming a nucleus bulk density of 400 kg m^{-3} , a 100% water comet, and that the production rate remained at the level from our last observation through perihelion, the total water mass loss through perihelion, gives a minimum size of the nucleus required to produce the amount of water sublimating to have a radius of 280 meters. Assuming that the comet was only one-half or one-third water by mass, the sphere radius becomes 350 m and 400 m, respectively. Alternatively, the active area on day -35.78 can be used, making the same three assumptions of all, one-half and one-third water by mass giving maximum estimates of the spherical nucleus radius of 720 m, 1020 m, and 1250 m. These latter estimates assume all the activity before November 9 was due to direct water-driven sublimation of the nucleus and do not account for the possibility that the comet was already releasing a fraction of icy fragments before that date. These results are summarized in Table 3.

4. SUMMARY

The SWAN all-sky H Ly α camera on the *SOHO* spacecraft observed the hydrogen coma of the new Oort Cloud Sun-grazing comet 2012 S1 (ISON) during most of the last month of its activity before perihelion on 2013 November 28. Water production rates were calculated from each image and daily average water production rates from the vicinity of the nucleus were calculated from the combined analysis of all the images using the inherent temporal information in the extended hydrogen coma in the large FOV of SWAN. The activity was consistent with water-driven sublimation from a small nucleus with an equivalent spherical radius in the range of 0.3–1.3 km from October 23 until November 12. Given the pre-perihelion variation of water production rate before the final two weeks, the variation was not atypical of other new Oort Cloud comets. For example C/2011 L4 (PanSTARRS) behaved similarly to other new comets (Combi et al. 2014) like C/2002 T7 (LINEAR) (Combi et al. 2009) in that their variation with heliocentric distance had a power-law slope flatter than r^{-2} before perihelion but slightly steeper than r^{-2} after. On November 12 the nucleus started massively shedding fragments that greatly increased the total active surface area to more than ten times the original surface area of the nucleus itself. This could have been due as suggested by Li et al. (2013) to the possibility that a large portion of the nucleus was not in sunlight throughout most of the inbound pre-perihelion part of its orbit, but then was rotated into full sunlight on or about November 12. The resulting rapid release of volatile material and eventually of the entire mass of the nucleus led to its eventual total disruption by perihelion. It behaved unlike another disintegrated comet C/1999 S4 (LINEAR), which seemed to disintegrate in one large event and then the fragments released simply sublimated away over the next few weeks (Mäkinen et al. 2001a).

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