OUTGASSING BEHAVIOR OF C/2012 S1 (ISON) FROM 2011 SEPTEMBER TO 2013 JUNE

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ABSTRACT

We report photometric observations for comet C/2012 S1 (ISON) obtained during the period time immediately after discovery (r = 6.28 AU) until it moved into solar conjunction in mid-2013 June using the UH2.2 m, and Gemini North 8 m telescopes on Mauna Kea, the Lowell 1.8 m in Flagstaff, the Calar Alto 1.2 m telescope in Spain, the VYSOS-5 telescopes on Mauna Loa Hawaii and data from the CARA network. Additional pre-discovery data from the Pan STARRS1 survey extends the light curve back to 2011 September 30 (r = 9.4 AU). The images showed a similar tail morphology due to small micron sized particles throughout 2013. Observations at submillimeter wavelengths using the James Clerk Maxwell Telescope on 15 nights between 2013 March 9 (r = 4.52 AU) and June 16 (r = 3.35 AU) were used to search for CO and HCN rotation lines. No gas was detected, with upper limits for CO ranging between 3.5–4.5 × 1017 molecules s−1. Combined with published water production rate estimates we have generated ice sublimation models consistent with the photometric light curve. The inbound light curve is likely controlled by sublimation of CO2. At these distances water is not a strong contributor to the outgassing. We also infer that there was a long slow outburst of activity beginning in late 2011 peaking in mid-2013 January (r ~ 5 AU) at which point the activity decreased again through 2013 June. We suggest that this outburst was driven by CO injecting large water ice grains into the coma. Observations as the comet came out of solar conjunction seem to confirm our models.

Key words: comets: general – comets: individual (ISON)

Online-only material: machine-readable table

1. INTRODUCTION

On 2012 September 21 a new sungrazing comet was discovered using the 0.4 m International Scientific Optical Network telescope in Russia (Nevski & Novichonok 2012). The comet was designated C/2012 S1 (ISON, hereafter comet ISON) and was bright and active at 6.3 AU pre-perihelion. The current estimate of its orbital eccentricity is 1.000004, thus it is possibly making its first passage through the inner solar system from the Oort Cloud. Perihelion is on 2013 November 28 at a distance of 0.0125 AU (2.7 solar radii), and some predictions suggest it could become exceedingly bright. About a dozen comets in the past ~270 yr have been spectacularly bright (mag < ~5), and the hope that comet ISON could be one of these has generated intense scientific interest. However, it is difficult to predict the comet’s behavior while still far from the Sun. Comet ISON was well placed for observation until moving into solar conjunction in late 2013 August, near r = 2.4 AU. In this Letter, we report observations of the comet at optical and submillimeter wavelengths from 2011 September through 2013 June. Based on these data and the gas production rates from the literature, we used an ice sublimation model to look at activity scenarios for when the comet emerged from solar conjunction.

2. OBSERVATIONS AND DATA REDUCTION

We initiated both a pre-perihelion imaging campaign and a submillimeter observing campaign to constrain volatile production rates (see Table 1). Imaging data were taken on both photometric nights and nights with some cirrus. Calibrations on photometric nights were accomplished with measurements...
of Landolt (1992) standard stars. Fields on non-photometric
nights and for Pan-STARRS1 (PS1) were calibrated against the
Sloan Digital Sky Survey (SDSS; York et al. (2000)) or the PS1
nights and for Pan-STARRS1 (PS1) were calibrated against the

Notes.

a Number of exposures.
b Total integration time, s.
c Heliocentric distance, AU.
d Geocentric distance, AU.
e Solar phase angle, degrees.
f True anomaly, degrees.
g Position angle of the antisolar vector, degrees east of north.
h Position angle of the negative velocity vector, degrees east of north.
i Mean apparent R-band magnitude.
j Hereford Arizona Observatory.
k Rest Frequency, in GHz.
l Total integration time, s.
m Main beam efficiency.
n 1σ rms noise in unit of the main beam brightness temperature, in mK.
p Kinetic temperature computed based on the formula from Biver et al. (1997), in K.
q Production rates upper limits for CO, in \(10^{27}\) molecules s\(^{-1}\).

Table 1

<table>
<thead>
<tr>
<th>UT Date</th>
<th>Telescope</th>
<th>N(^a)</th>
<th>(r^b)</th>
<th>Filter</th>
<th>(\Delta^d)</th>
<th>(\alpha^e)</th>
<th>TA(^f)</th>
<th>PA_{\alpha}^{-}(^g)</th>
<th>PA_{\alpha}^{-}(^h)</th>
<th>(m)(^i)</th>
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<td>180</td>
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<td>(i_{P1})</td>
<td>9.064</td>
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<td>900</td>
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<td>r</td>
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<td>197</td>
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<td>135</td>
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<td>r</td>
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<td>2.487</td>
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<td>7.88</td>
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<td>294.2</td>
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<td>309.1</td>
<td>14.71</td>
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Comet ISON was detected in images obtained with PS1 and the Gigapixel Camera 1 (0’256 pixels) between 2011
September and 2013 January during regular survey operations. Exposures were made in the survey \(grizw_{P1}\) filters. Moving objects are normally automatically detected and measured via difference imaging (Denneau et al. 2013). Before 2012 January the comet was moving too slowly and/or was too faint for this to be successful; these detections were made by manual inspection of the data post-discovery. In all PS1 pre-discovery data the comet has a profile no wider than the point spread function (PSF) of field stars, although we infer it was likely to be active at this time (see Section 3.2). The magnitudes were measured via DAOPHOT PSF-photometry relative to field stars of known magnitudes (Schlafly et al. 2012). The 2012 January 28 detections were reported to the Minor Planet Center within 24 hr. However as its motion was roughly parallel to

http://www.sdss.org/
Figure 1. Images of comet ISON obtained using the Gemini 8 m with GMOS on 2013 February 4, March 4, April 3, May 4 and 30 through an r filter. The May 4 image is a color composite image made using the g, r and i filters. East is left, N is up and the FOV is ~2.5 wide per panel (corresponding to a projected distance of 4.25–4.70 × 10^3 km at the distance of the comet).

the ecliptic, and the PSF was measured to be stellar, it was not reported as an object of interest. From 2012 September onward the comet possessed a visible coma, and magnitudes were measured in the PS1 photometric system within a 5′′ radius circular aperture (Schlafly et al. 2012; Magnier et al. 2013) when not contaminated by field stars.

2.2. UH2.2 m, HCT2 m, Lowell Observatory 1.8 m, and Calar Alto 1.2 m

We had several observing runs in 2012–2013 where we obtained data on comet ISON. The UH2.2 m telescope on Mauna Kea was used with the Tek 2K CCD camera and Kron–Cousins filter. Data were obtained using the Himalayan Chandra telescope with the optical 2K×4K imager (E2V chips with image scale of 0′′.17 pixel^−1) through Bessell R-band filters. Observations at the Lowell observatory were taken on the Perkins 1.8 m telescope with the PRISM reimaging camera (SITE 2K×2K CCD) through the Bessell R band. Data were obtained under variable conditions during several nights using the Calar Alto 1.2 m with the E2V CCD binned 2 × 2.

2.3. Gemini North 8 m

Director’s discretionary time was awarded to image the comet monthly from 2013 February through June (see Figure 1). Data were obtained using the GMOS-N multi-object spectrograph in imaging mode with the E2V CCD binned 2 × 2 resulting in a plate scale of 0′′.145 pixel^−1. Baseline calibrations were used in the reduction. Most of the images were obtained through the Sloan r′-filter (Fukugita et al. 1996). Some non-photometric nights were calibrated using the USNO-A2 catalog, resulting in a photometric accuracy of 5%–10%.

2.4. JCMT

The radio observations were performed using the 15 m James Clerk Maxwell Telescope (JCMT) on 15 days between 2013 March 9 through 2013 June 16. Long integration observations were performed on March 15 and 30, April 1, 27–29 and June 14–16. At other times, hourly snapshot observations were obtained. We used HARPS and the R×A3 heterodyne receivers in beam-switch (i.e., secondary chopping) mode. The planets Mars and Uranus were frequently observed to monitor the main beam efficiency. The ACSIS spectrometer was used, which provides a total bandwidth of 250 MHz and a spectral channel spacing of 30.5 kHz. The data were reduced using a combination of the Star-link software and IDL scripts.

Searches for the J = 3–2 and J = 2–1 rotational transitions of CO gas and the J = 4–3 and J = 3–2 transitions of HCN gas returned negative results. HCN is an indicator of sublimated gas, but not expected to play a major role in controlling the brightness of the comet, so we focus only on the analysis of CO. To estimate production rates of CO, we measured the root-mean-square value of the main beam brightness temperature fluctuations within ±10 km s^−1 of zero velocity (see Table 1). Given that CO lines are likely to be narrow (Senay & Hewitt 1994; Biver et al. 2002), the 3σ upper limits to the line area were derived within a 1.2 km s^−1 or 1.5 km s^−1 (for June only) band. We assume that gas molecules escape from the surface at a constant velocity and follow a Hase density distribution. We adopted an average expansion velocity of 1.12 r^−0.41 km s^−1 and the kinetic temperature was estimated using an empirical formula of 116–r^1.24 K, where r is the heliocentric distance (Biver et al. 1997). The derived production rate upper limits, for the CO J(2−1) and J(3−2) transitions, are listed in Table 1.

2.5. The CARA Project

CARA is a consortium of amateur astronomers who have developed a standardized approach to observing comets. Photometry through a Cousins R-filter was obtained on 46 dates (Table 2) beginning shortly after discovery in 2012 September through 2013 May 2 with most of the observations coming from 0.4 m telescopes at the BRIXIIS Observatory in Belgium, the Talmassons Observatory and Stazione Astronomica Descartes in Italy. The photometry was calibrated using the APASS catalog. 19

2.6. VYSOS Telescope

We used the 5.3 inch Variable Young Stellar Objects Survey (VYSOS) program20 robotic refractor at the Mauna Loa Observatory in Hawai‘i, with an Apogee Alta U16M CCD (field of view 2.9 × 2.9 degrees with a plate scale of 2′:53 pixel^−1) to image the comet. Images were taken nearly nightly from 2013 April to mid-June (Table 2). On most nights, at least three exposures of 100 s each were taken in a Sloan r′-band filter. We used Sextractor21 to extract detections from our 165 VYSOS images, using an aperture that contained >95% of the PSF. We corrected for focal plane irregularities with an approximate distortion map, permitting us to match stellar detections between frames in the VYSOS run. We used the first image to perform relative photometric calibrations of subsequent images, and used overlapping stars from frame to frame for calibration—thus establishing a relative zero-point calibration spanning the entire run has a nominal uncertainty of 0.027 mag. For some VYSOS frames, the survey overlapped with SDSS, permitting us to calibrate one selected frame to 0.014 mag using 39 SDSS stars, establishing an absolute magnitude scale for the entire run. ISON’s ephemeris was used to search for it in the Sextractor catalogs and then measure it, finding an object within 4′′ (<2 pixels) of its predicted location in 129 frames (the others were excluded because of chip gaps and field star proximity).

3. ANALYSIS AND RESULTS

3.1. Finson–Probstein Dust Modeling

Finson–Probstein modeling (Finson & Probstein 1968) was used to analyze the synchrone–syndyne pattern and the optical

http://www.aaavso.org/apass
http://www.ifa.hawaii.edu/~reipurth/VYSOS/
http://www.astromatic.net
appearance of the comet’s dust environment (modeling details are described in Beisser 1987; Vincent 2010). Due to projection, as seen from Earth the synodyne–synchrope pattern converges in the direction of the dust tail, aligning with the central axis of the optical dust tail. The travel time of micron-sized dust through the dust tail in the images is ~20–30 days. Larger grains of ~100 μm size may stay much longer (~100 days) in the immediate (5" radius) neighborhood of the nucleus. The width of the dust tail suggests a dust expansion speed of ~10 m s\(^{-1}\) assuming micron size dust grains dominate its optical appearance. It is reasonable to assume that larger (100 μm) grains leave the nucleus dust acceleration zone at a speed near one to a few m s\(^{-1}\).

### 3.2. Conceptual Ice Sublimation Model

We used a simplified ice sublimation model to investigate the level of activity versus heliocentric distance. The model computes the amount of gas sublimating from an icy surface exposed to solar heating (Meech et al. 1986; Meech & Soren 2004). As the ice sublimates, either from the nucleus surface or near-subsurface, the escaping gas entrains dust in the flow which escapes into the coma and tail. The scattered brightness of the comet as measured from Earth has a contribution from the light scattered from the nucleus and the dust. Model free parameters include the ice type, nucleus radius, albedo, emissivity, density, properties of the dust (sizes, density, phase function), and fractional active area.

Our model assumes a nucleus radius of \(R_N \sim 2 \text{ km}\), consistent with the size limit inferred from Hubble Space Telescope (HST) measurements (Li et al. 2013), an albedo of 0.04 for both the nucleus and dust, and a linear phase function of 0.04 mag deg\(^{-1}\) typical of other comets. We assume a nucleus density of 400 kg m\(^{-3}\) similar to that seen for comet 9P/Tempe1 and 103P/Hartley 2 (Thomas et al. 2013a, 2013b), a grain density of 1000 kg m\(^{-3}\), and micron-sized grains (see Section 3.1 and Yang 2013). Because of the many model free parameters, our conclusions are dependent on how well we can constrain some of the values with observations. The shape of the light curve—i.e., where the curve is steep or shallow—is determined by the sublimating ice composition. With reasonable estimates of nucleus size, albedo, density, and grain properties, the fractional active surface area is adjusted to produce the observed volatile production rates. Note, if the \(HST\) nucleus size is much smaller than the upper limit used here, the model will require an increase in the active fractional area, but otherwise the discussion below remains unchanged.

Because the comet was active at discovery (\(r = 6.3 \text{ AU}\)) where it was too cold for significant water-ice sublimation, there must be another volatile besides \(H_2O\) responsible for the outgassing. The likely candidates are CO and CO\(_2\). The warm \Spitzer\ measurements on June 13 (Lisse et al. 2013) detected an excess brightness at 4.5 μm due to emission from a neutral gas coma which could either be due to CO\(_2\) or CO (because both have lines in the bandpass). Unfortunately, there have been no definitive spectral detections of either molecule reported yet, however the similarity of the estimated CO\(_2\) production rate to measurements of other comets at large distances (Ootsubo et al. 2012) suggested that CO\(_2\) dominated. We ran two models, assuming the excess seen by \Spitzer\ was either all CO or CO\(_2\) (see Table 3) and the best fit models are shown in Figure 2(a). While both models can fit the inferred \Spitzer\ and water production rates, and match the scattered light data from the dust in 2013 June, neither model alone is a good match to the light curve.

Our June CO production upper limits (which agreed with preliminary estimates from \HST\; M. A’Hearn 2013, private communication), also suggested that the \Spitzer\ observations were mostly CO\(_2\). With this scenario, however, the only explanation for the light curve between 6–3.5 AU was a long slow outburst, driven most likely by CO (and supported by a possible CO detection; N. Biver 2013, private communication). Such a scenario is physically plausible, as evidenced by the aperiodic CO driven outbursts of Comet 29P/Schwassmann-Wachmann 1 at similar distances (Cochran et al. 1982; Crovisier et al. 1995).

While we were preparing the models, an amateur astronomer, B. Gary\(^{22}\) reported the recovery of the comet as it came out of solar conjunction on 2013 August 12 and 16 at 7 airmasses. These magnitudes are also included in Table 1. At \(r = 2.5 \text{ AU}\), \(H_2O\) sublimation should be important and we added this to the model and found that with a fractional active area of 2.5% for water sublimation and 0.54% for CO\(_2\), the model fit both the 2013 August data and the early PS1 data with the comet being largely controlled by CO\(_2\) outgassing as shown in Figure 2(b).

\(^{22}\) brucegary.net/ISON
If we allow that solar heat from the inbound orbit reached a deeper layer of CO this could trigger additional outgassing starting around the time of the first PS1 observations. The effect was a period of increased activity reaching a maximum effective sublimating area of \( \sim \)1.5 m\(^2\) on the day of the first observations. The H\(_2\)O production rate on that date was approximately \( 1 \times \)10\(^3\) molecules s\(^{-1}\). This increase is shown as the dotted line in Figure 2(b). The difference between the observations and the CO\(_2\) plus H\(_2\)O model is shown in Figure 2(c) which represents the CO outburst. The predicted CO production rates during this time are shown in Table 3.

Matching water production estimates from 2013 March 5 and May 4 (Schleicher 2013a, 2013b; see Table 3), required that the effective water-ice sublimating area was \( \sim \)6\( \times \) that of the nucleus surface in March dropping to \( \sim \)80% of the surface in May as the heliocentric distance decreased. The model run-out was also consistent with all of the other H\(_2\)O production rate upper limits shown in Table 3. As was seen for 103P/Hartley 2 (A’Hearn et al. 2011), we propose that this outburst ejected large water ice grains into the coma. It has been shown experimentally that sublimation from deeper layers can result in the ejection of large slow-moving grains (Lauffer et al. 2005). A long-lived population of large (\( \sim \)100 \(\mu\)m) water-ice grains in the near nucleus environment could explain this water production behavior.

Dirty (low albedo) ice grains of this size could survive for months at the low temperatures outside \( r = 8 \) AU, however inside 6 AU they would not survive very long (Hanner 1981). On the other hand, for moderately high albedo grains (\( p_e > 0.5 \)) lifetimes of months to days are possible from \( r = 6 \) to 3.5 AU (2012 September through 2013 May). As noted in Section 3.1, grains this large would not contribute optically to the tail structure as they would remain close to the nucleus in projection. Once in the coma, the water ice grains slowly sublimate, releasing dust into the coma and increasing its cross section. With high albedos and long grain lifetimes, the duration of the brightening by this mechanism could be many months (e.g., 2012 January–2013 January). The fading was not caused by loss of large grains from the aperture, grains that would survive for the duration are so large that they stay within the 5\(^{\circ}\) radius aperture (equivalent to \( \sim 15,000 \) km) in 2013 January. At a typical velocity of 1 m s\(^{-1}\) the crossing time for the aperture is \( \sim \)months. The effective brightness decline (compared to an expected increase from sublimation as \( r \) decreased) was thus a loss of cross section within the aperture. With the limited data we have, we cannot say if the outburst was short-lived, or if there was continued activity, although possible detections of CO after 2013 January suggest that there was outgassing for a period of time.

### Table 3

<table>
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<th>UT Date 2013</th>
<th>JD(^a)</th>
<th>( J )(^b)</th>
<th>( T )(^c)</th>
<th>( Q_{\text{CO}} )( d)</th>
<th>( Q_{\text{CO}} )( e)</th>
<th>Facility</th>
<th>Ref</th>
<th>Model ( Q_{\text{CO}} )( f)</th>
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<td>1E28</td>
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</tr>
<tr>
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<td>-175.80</td>
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<td>3</td>
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</tr>
</tbody>
</table>

**Notes.**

\( ^{a} \) Julian Date: 2,400,000.

\( ^{b} \) Heliocentric distance, AU.

\( ^{c} \) True anomaly, degrees.

\( ^{d} \) Production rate, molecules s\(^{-1}\).

\( ^{e} \) CO production rate prediction from model CO outburst.

**References.** (1) Bodewits et al. 2013; (2) Schleicher 2013a; (3) This Letter; (4) M. A’Hearn 2013, private communication; (5) Schleicher 2013b; (6) Lisse et al. 2013.

### 4. DISCUSSION

In formulating the concept of the Oort Cloud (Oort & Schmidt 1951), Oort suggested that the dearth of returning long-period comets at large semi-major axis was due to chemical alteration of their surface layers by cosmic rays, and that this “volatile frosting” was lost on the first passage through the inner solar system. One interpretation of comet ISON’s heliocentric light curve could be its activity through 2013 January was dominated by the loss of this highly volatile layer, and the activity since then has been decreasing. The implication of this interpretation is that the comet will not brighten as dramatically as hoped near perihelion, and that the apparent brightness coming out of solar conjunction would have remained flat or even decreased. This is similar to the behavior observed for Comet C/1973 E1 (Kohoutek).

In the second scenario for activity where the comet is largely driven by CO\(_2\) outgassing, our models predicted that the apparent brightness within a 5\(^{\circ}\) radius aperture should be \( \sim R = 14\sim 14.5 \) when the comet came out of solar conjunction in late August/early September matching closely what has occurred. While it is unwise to make predictions about the brightness at perihelion when the comet is still far from the Sun, especially when it will pass so close to the Sun, the run out of these sublimation models show that the comet can still be quite bright at perihelion.

Gemini is operated by AURA under a cooperative agreement with the NSF on behalf of the Gemini partnership. The James Clerk Maxell Telescope is operated by the Joint Astronomy...
Figure 2. Conceptual ice sublimation model, showing the best fit for 2013 June 13 (TA = −173.0). The different ice models are for H$_2$O (dot-dash), CO$_2$ (long-short dash), CO (dotted) and total (solid red line). The large telescope photometric measurements are shown as large black squares, the PS1 precovery data as blue squares, the CARA data as cyan triangles, the data from VYSOS as the magenta crosses, and data as reported in the MPECs as black dots (uncorrected for aperture size). The optical data obtained at the time of the Spitzer observations (Lisse et al. 2013) are shown as small red squares. The reported measurements by B. Gary are shown as black triangles. The vertical dotted lines show the dates for which Q$_{H2O}$ has been published. The vertical long dashed lines show the dates where we present JCMT Q$_{CO}$ upper limits and the short dashed lines indicate when the comet will likely become accessible to large telescopes as it comes out of solar conjunction. (a) Best fit models assuming that all the reported Spitzer outgassing is due to only CO or CO$_2$. (b) Best fit model with baseline CO$_2$ plus H$_2$O sublimation with an additional slow CO outburst. (c) Difference between the data and sublimation model, showing the outburst.