FAR-ULTRAVIOLET OBSERVATIONS OF COMET C/2012 S1 (ISON) FROM FORTIS

Stephan R. McCandless1, Paul D. Feldman1, Harold Weaver2, Brian Fleming3, Keith Redwine1, Mary J. Li1, Alexander Kutyrev4, and S. Harvey Moseley4

1 Department of Physics and Astronomy, The Johns Hopkins University, Baltimore, MD 21218, USA; stephan@pha.jhu.edu
2 Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723, USA
3 Center for Astrophysics and Space Astronomy, University of Colorado, Boulder, CO 80309, USA
4 Goddard Space Flight Center, Greenbelt, MD 20771, USA

Received 2016 April 27; revised 2016 June 16; accepted 2016 June 17; published 2016 August 26

ABSTRACT

We have used the unique far-UV imaging capability offered by a sounding-rocket-borne instrument to acquire observations of C/2012 S1 (ISON) when its angular separation with respect to the Sun was 26°.3 on 2013 November 20.49. At the time of observation, the comet’s heliocentric distance and velocity relative to the Sun were \( r_h = 0.43 \) au and \( v_h = -62.7 \) km s\(^{-1}\). Images dominated by C1 \( \lambda 1657 \) and H1 \( \lambda 1216 \) were acquired over a \( 10^6 \times 10^6 \) km\(^2\) region. The water production rate implied by the Ly\(\alpha\) observations is constrained to be \( Q_{\text{H}_2\text{O}} \approx 8 \times 10^{29} \) s\(^{-1}\), while the neutral carbon production rate was \( Q_{\text{C}} \approx 4 \times 10^{28} \) s\(^{-1}\). The radial profile of C1 was consistent with it being a dissociation product of a parent molecule with a lifetime \( \tau \approx 5 \times 10^5 \) s, favoring a parent other than CO. We constrain the \( Q_{\text{CO}} \) production rate to \( 5^{+1.5}_{-1.3} \times 10^{28} \) s\(^{-1}\) with 1\(\sigma\) errors derived from photon statistics. The upper limit on the \( Q_{\text{CO}}/Q_{\text{H}_2\text{O}} \) is \( \leq 6\%\).

Key words: comets: general – comets: individual (C/2012 S1 (ISON)), C/2001 Q4 (NEAT), C/2004 Q2 (MACHHOLZ) – molecular processes – Oort Cloud

1. INTRODUCTION

The recent apparition of comet C/2012 S1 (ISON) presented a unique opportunity to observe a dynamically new, sungrazing, Oort cloud comet (Oort 1950) prior to its reaching perihelion on 2013 November 28 2013 at a distance of only 2.7 au and \( v_h = -62.7 \) km s\(^{-1}\). The initial gas production of an Oort cloud comet undergoing its first passage into the inner solar system is expected to be dominated by an excess “frosting” of volatile ices. This frosting is thought to have been created over a solar lifetime (~4.6 Gyr) through the bombardment of the comet’s icy surface by a flux of interstellar dust, cosmic rays, ultraviolet, and X-ray radiation in the nether regions between the outermost solar system and the interstellar medium (Whipple 1950, 1951, 1978; Oort & Schmidt 1951). It is further thought that if the frosting is thin enough, then the mass sublimation process, precipitated by the steady increase in the radiation environment upon ingress toward the Sun, will gradually reveal a surface composition that is primordial in nature.

The ingress of ISON was closely followed by a global network of amateur and professional observers shortly after its discovery by Novski et al. (2012). Sekanina & Kracht (2014) have prepared a comprehensive review and model of its photometric and water production behavior, starting with the pre-discovery photometry and extending beyond its total disintegration at 5.2 \( R_\odot \approx 3.5 \) hr prior to perihelion. The observations reveal that the photometric variations and water production rates were on a seesaw cycle of coma expansion and depletion on ever shortening timescales throughout ingress. Five cycles were identified up to 2013 November 12.9. Disintegration was presaged by two major fragmentation events, led by a 10-fold increase in the observed water production rates between November 12.9 and 16.6, and followed by a 5-fold increase between November 19.6 and 21.6 (Combi et al. 2014).

These water production rates were derived from observations made by the Solar Wind Anisotropies (SWAN) Ly\(\alpha\) camera on the Solar and Heliospheric Observer satellite, which provides daily all sky coverage of Ly\(\alpha\) emissions with \( 1^\circ \times 1^\circ \) resolution from its vantage at Earth–Sun Lagrange point 1. Consequently, SWAN water production observations typically lag those made using small apertures, such as those from the Cryogenic Echelle Spectrometer (CSHELL) at the NASA InfraRed Telescope Facility (IRTF) acquired by DiSanti et al. (2016). CSHELL observations, which were acquired through a \( 1^\circ 0 \times 3^\circ 0 \) slit, show water production dropping by factor of \( >5\) between November 15 and 16, coincident with a drop in the visible light curve that marked the cessation of activity from event 1 as described by Sekanina & Kracht (2014).

We report here on far-UV observations over a \( 30' \times 30' \) field of view (FOV) from a sounding-rocket-borne spectro/ telescope made in the intervening period of the second event on November 20.49. They serve as a probe of water production on spatial scales intermediate to those provided by CSHELL and SWAN.

Sounding rockets offer a unique platform for observing the far-UV emission of cometary bodies in close proximity to the Sun. The far-UV bandpass provides access to a particularly rich set of spectral diagnostics for determining the production rates of CO, H, C, O, and S. Safety concerns for Hubble Space Telescope (HST) restrict its use to solar elongation angles of \( >50^\circ \), translating to heliocentric distances of \( >0.766 \) au in the case of ISON. In contrast, sounding-rocket-borne instruments can use the Earth’s limb to occult the Sun. The observations of ISON described here were made at an elongation of 26°3 when the comet was at a heliocentric distance of \( r_h = 0.43 \) au, a heliocentric velocity of \( v_h = -62.7 \) km s\(^{-1}\), a separation between the Earth and comet of \( \Delta = 0.84 \) au, and a relative velocity with respect to Earth of \( \Delta = -4.5 \) km s\(^{-1}\).
2. FORTIS INSTRUMENT OVERVIEW AND CALIBRATION

FORTIS (Far-uv Off Rowland-circle Telescope for Imaging and Spectroscopy; McCandliss et al. 2004, 2008, 2010; Fleming et al. 2011) is a 0.5 m diameter //10 Gregorian telescope (concave primary and secondary optics) with a
diffractive triaxially figured secondary, creating an on-axis imaging channel and two redundant off-axis spectral channels
that share a common focal plane. The spectral channels have an
inverse linear dispersion of 20 Å mm\(^{-1}\). The spectral bandpass is \(\sim\)800–1800 Å. The imaging plate scale is 41\('\)′.25 mm\(^{-1}\). The FOV is (0′.5)\(^2\).

A programable multi-object capability is provided by a
microshutter array (MSA) placed at the prime focus of the
telescope. The MSA has 43 rows \(\times 86\) columns in the FOV.
An experimental target acquisition system, is designed to
operate autonomously with the intent of limiting spectral
confusion by closing all but one column on each of the 43
rows. Each individual shutter subtends a solid angle of
\(\Omega = 12\' 4 \times 36\' 9\).

Our flight MSA was derived from prototype versions of the
large area arrays developed at Goddard Space Flight Center for
use in the Near Infrared Spectrograph on the James Webb
Space Telescope (Li 2005). The shutters are opened with the
help of a magnet that passes in front of the array, timed to
coincide with a serial stream of opening voltages. Shutters are
closed by reversing the direction of the magnet and applying
closing voltages.

The three channel microchannel plate (MCP) detector,
custom built by Sensor Sciences, employs separate sets of
crossed delay-line readout-anodes fed by \(z\)-stack MCPs with
CsI photocathode inputs. The deadtime of the pulse counting
electronics is 400 ns, however, the maximum count rate of each
channel is limited by the telemetry clock rate of the first-in,
first-out (FIFO) buffer used to collect the pulse heights and
locations in \(x\) and \(y\). The pulse clock rate is 62.5 KHz for the
zero-order imaging channel and 125 KHz each spectral
channel. We refer to these channels as P1zero, P2minus and
P3plus.

The zero-order imager has a short wavelength cutoff
defined by the transmission of a CaF\(_2\), MgF\(_2\) cylindrical
doublet lens. The doublet is included to correct astigmatism in
the imager and limit background counts from the geocoronal
\(\text{Ly}_\alpha\). The slits in the MSA have a pitch of 1 mm \(\times 0.5\) mm in
the secondary focal plane. A few percent of the shutters are
not active due to shorts between columns and/or rows in the
array. These shorts are masked out to prevent drawing
excessive current that could potentially damage the array.
Figure 1 is an image of the active microshutters acquired
during pre-flight payload qualification testing. The illumination
source was a slow paraxial beam of Hg\(_\text{I}\) 1849 provided
by a penray lamp. Approximately 70\% of the shutters were
active.

The effective area of FORTIS was determined from
component level efficiency measurements pre- and post-flight
made with the Calibration and Test Equipment at JHU (Fastie
& Kerr 1975) following the procedures described by Flem
ing et al. (2013). The post-flight effective areas of the spectral
and imaging channels, shown in Figure 2, will be used for
this work.

3. OBSERVATIONS

JHU/NASA sounding rocket 36.296UG was launched from
LC-36 at White Sands Missile Range, New Mexico at
04:40 MST on 2013 November 20. The Black-Brant IX
delivery system carried our experimental spectro/telescope,
FORTIS, to an apogee of 270 km, providing 395 s of
exoatmospheric time above 100 km.

In flight, the plan for target acquisition was to observe the
comet for 30 s in the imaging channel through a fully open
MSA, and then deploy a preprogramed slit, in the shape of a K,
on the center of brightness. The location of the center of
brightness was to be determined by an on-the-fly peak locating
subsystem, serving as an interface between the zero-order
imager and MSA. Unfortunately, the preprogramed slit never
successfully deployed due to magnet and address timing issues,
frustrating our goal of acquiring confusion-limited spectral
information from selected regions in the coma along and across
the Sun-comet line in an effort to detect faint volatile species.

Nevertheless, zero-order images and dispersed spectral
images were acquired through a “mostly open” MSA, during
an \(\approx\)50 s interval ending \(\approx\)40 s before apogee. Three additional
attempts to deploy preprogramed slits at roughly 60 s intervals
resulted in a “partially open” MSA, having similar shutter
patterns wherein \(\approx\) half of the bottom half of the shutters
remained closed. A large block of open shutters surrounding
the comet allowed the extraction of radially averaged profiles
from the weaker emissions in the zero-order channel and “slit
averaged” profiles from the very strong emissions in the spectral
channels.

An additional complication arose in determining the true
count in the spectral channels. During much of the flight the
observed rate was saturated at the telemetry sample rate of
125 KHz. Fortunately, during the second attempt to deploy a
slit the count rate in the “P2minus” channel, which is the
slightly less-sensitive of the two, fell below the sample rate to
115 KHz in response to the smaller number of open shutters.
A modest deadtime correction factor of 1.16 was found post-flight
for the ratio of the true rate to the sampled rate. The correction
was determined in post-flight calibrations by taking advantage
of the linearity provided by a cesium iodide coated photo-
multiplier tube (PMT) in response to a steadily increasing
illumination from a deuterium lamp. A plot of the count rate
from the PMT against the count rate of a similarly illuminated
FIFO buffered MCP, clocked by telemetry, provided the
correction factor.

Representative data acquired pre-apogee and near reentry are
shown in Figure 3. The top panels show the on-axis, zero-order
imaging and off-axis spectral channels. The zero-order imaging
has been multiplied by 15 and a 1/4 root stretch has been
applied to elevate faint features. The bottom panels show the
projection of the images onto the X-axis, allowing assessment
of the background levels to be subtracted. The zero-order
imager has a significant background with respect to the
cometary signal. Initial background measurements were
acquired separately in the zero-order channel before arriving
at the comet. They were used as the basis of a model to account
for the background variations in the cometary images during
the course of the flight. The projected background model is
shown in red and the result from the subtraction is shown
in blue.

The spectral images are dominated by the intense emission
of cometary \(\text{Ly}_\alpha\), with has a peak brightness of 625 Krayleigh.
transitions, producing excited atoms or molecules that then re-emit into $4\pi$ sr. Line intensity varies with the square of the distance between the comet and the Sun ($r_0$). If there is a coincidence between the resonance absorption and a set of strong line emission within the solar spectrum, as is the case for C1, then the shape of the solar line profile and the relative velocity between the comet and the Sun become another important factor in modulating the fluorescence line intensity (Swings 1941). We have neglected the Greenstein effect (Greenstein 1958), wherein the differential velocity of the cometary outflow in the sunward and anti-sunward directions can produce an additional, second-order modulation in fluorescence line intensity. Our solar spectral energy distribution has too low a resolution to sufficiently account for the Greenstein effect.

The scattering efficiency for a transition, conventionally calculated at 1 au and commonly known as the “g-factor,” is given by

$$g_i(r_h) = \frac{\lambda_i^2 f_i \epsilon_i (r_h)}{m_e c^2} \frac{S_i}{A_i} \text{ photons s}^{-1},$$

(1)

where $\lambda_i$ is the wavelength, $f_i$ is the oscillator strength, and $\frac{S_i}{A_i}$ is the branching ratio for the excited transition (ratio of the $i$th transition de-excitation rate to the sum of all transitions out of the excited state). $F_{\odot}(r_h)$ is the solar photon flux at 1 au (photons cm$^{-2}$ s$^{-1}$ Å$^{-1}$) Doppler-shifted according to the appropriate heliocentric velocity, $r_h$. The above formula is valid for the optically thin case. A more sophisticated treatment models the absorbing transition as a Voigt profile integrated over the Doppler-shifted solar spectrum, and so in general the g-factor is also a function of column density. Optically thin g-factors are shown in Figure 4 for C1 $\lambda$1561, C1 $\lambda$1657, S1 $\lambda$1425, S1 $\lambda$1475, and O1 $\lambda$1304, panels (a) to (e), respectively. We see that C1 $\lambda$1657 is an order of magnitude stronger than all the others at the most negative velocities.

In Table 1, we list the optically thin 1 au g-factors used in this study for C1 $\lambda$1657, O1 $\lambda$1304, and H1 $\lambda$1216 calculated using a heliocentric velocity of $r_h = -62.7$ km s$^{-1}$. We also show representative g-factors for the strongest two CO A-X bands (1-0) at 1510 Å and (2-0) at 1478 Å. The CO bands are pumped by continuum photons. A solar spectral energy distribution associated with a moderately active F10.7 cm flux of $\sim$150 sfu (solar flux unit),$^5$ as appropriate to the time of observation, was used for the C1 $\lambda$1657 and O1 $\lambda$1304 g-factor calculations. The H1 $\lambda$1216 g-factor was interpolated from Table 1 of Combi et al. (2014).

The scattering takes place into $4\pi$ sr, so that the brightness (in rayleighs)$^6$ of a comet emission line at arbitrary heliocentric distance is given by

$$B_i = \frac{\bar{N} g_i}{10^6 r_h^2},$$

(2)

where $\bar{N}$ is the mean column density (cm$^{-2}$). If all of the emission from the comet can be contained within an aperture whose solid angle $\Omega$ subbands an area $A_{\text{aper}} = \Omega \Delta^2$ at the

$^5$ 1 sfu = $10^4$ Ly = $10^{-55}$ erg cm$^{-2}$ s$^{-1}$ Hz$^{-1}$.

$^6$ Rayleigh $\equiv 10^6/(4\pi)$ photons cm$^{-2}$ s$^{-1}$ sr$^{-1}$.
Figure 3. Sets of spectral and imaging data. Pre-apogee sets acquired between $T + 192$ and $T + 247$ seconds are on top. Downleg sets acquired just prior to reentry between $T + 438$ and $T + 462$ seconds are on the bottom. X-axes projections are displayed underneath each image to assess background (see text for details). The zero-order images have been multiplied by a factor of 15 with respect to the spectral channels. A $1/4$ root power-law stretch has been applied to all images to elevate faint features.
Figure 4. Optically thin g-factors accounting for the Swings effect (modulation of the fluorescence line strength by Doppler shifting of the solar pumping line in and out of resonance with the absorbing transition in the comet), in the C I \( \lambda\lambda 1561, 1657 \) (panels (a), (b)), S I \( \lambda\lambda 1425, 1475 \) (panels (c), (d)), and O I \( \lambda 1304 \) multiplets (panel (e)). O I \( \lambda 1304 \) is pumped directly by the solar multiplet and indirectly through the coincidence of solar Ly\( \beta \) with O I \( \lambda 1026 \), which decays though O I \( \lambda 11287 \) and O I \( \lambda 8446 \) before reaching O I \( \lambda 1304 \); a mechanism known as Bowen (1947) fluorescence.
The shape of the pre-apogee profile is best represented by the upper envelope of each profile. Comparison to steady-state Haser models implies a water production rate between 4 × 10$^{27}$ s$^{-1}$ at small radii, while the larger radii are better matched by a lower rate of 2 × 10$^{27}$ s$^{-1}$. The disagreement with the steady-state models suggests a strongly increasing in the water production rate.

### Table 1

| Species | Wavelength | g-factor |
|---------|------------|----------|
| CI      | 1657       | 3.2 × 10$^{-5}$ |
| CO A 1Π−X 1Σ+(1-0)$^a$ | 1510       | 1.9 × 10$^{-7}$ |
| CO A 1Π−X 1Σ+(2-0)$^a$ | 1478       | 1.8 × 10$^{-7}$ |
| CO A 1Π−X 1Σ+(all bands)$^a$ | 1280−1800  | 1.5 × 10$^{-6}$ |
| S I     | 1474       | 1.1 × 10$^{-6}$ |
| O I     | 1302       | 6.0 × 10$^{-7}$ |
| H I$^b$ | 1216       | 2.2 × 10$^{-3}$ |

Notes.

$^a$ CO bands are pumped by solar continuum.

$^b$ Taken from Combi et al. (2014).

Figure 5. Lyα profiles summed over a 41′′25′′ wide slit centered on the comet. The profile in red was acquired pre-apogee between T+190 and T+240 seconds when the MSA was in a fully open state. In this state, the count rate was saturated at the maximum sample rate (125 kHz). The profile in black was acquired post-apogee between T+280 and T+340 seconds when an attempted addressing of a slit resulted in a partially opened MSA. This lowered the detected count rate below that of the sample rate, allowing an accurate deadtime correction to be made. The peak of the post-apogee profile is our most accurate estimate of the central Lyα brightness as sampled over 2″. The pre-apogee profile has been scaled so that its peak matches the post-apogee observation. The shape of the pre-apogee profile has fewer closed shutters, providing a smoother sample of the profile in comparison to the post-apogee profile. The true profile is best represented by the upper envelope of each profile. Comparison to steady-state Haser models implies a water production rate between 4 × 10$^{27}$ s$^{-1}$ at small radii, while the larger radii are better matched by a lower rate of 2 × 10$^{27}$ s$^{-1}$. The disagreement with the steady-state models suggests a strongly increasing in the water production rate.

Figure 6. Zero-order image zoom-in to ±1e5 km (332° × 332°). The observation intervals, post launch, are indicated above each image.

The Astronomical Journal, 152:65 (10pp), 2016 September

McCandless et al.

[\text{Figure 6.}]

where $\tau$ is the lifetime of the species in question. In general, the photodissociation lifetime of a species is proportional to the incident solar flux, and so $\tau_i$ will scale with heliocentric distance $r_i$.

In cases where the emissions are extended with respect to the aperture, it is common to model parent species, like CO, as a steady-state outflow from the nuclear regions of the coma, having a constant velocity $v$ and an exponential scale length (Haser 1957). The number density as a function of radius $r_c$ is given as

$$n = \frac{Q}{4\pi v \beta \tau c} \exp(-\beta r_c),$$

where $\beta = (\nu \tau)^{-1}$ is the inverse scale length. This model can be projected onto the line of sight to yield a column density, so a plot of the brightness as a function of radius yields a column density profile from which the product rates for the volatile species can be determined. A more sophisticated vectorial model (Festou 1981) accounts for the production of daughter products, emitted isotropically in the rest frame of the dissociating parent species.

### 4.2. Water Production Rate from Lyα Image

Water (H$_2$O) is well known to be the dominant volatile constituent of comets. Upon sublimation, the parent molecule H$_2$O dissociates into its atomic and molecular constituents, referred to as daughter products, under the influence of solar photons and solar wind particles. Budzien et al. (1994) have provided a thorough discussion of the various water destruction channels, including techniques to account for varying levels of extreme- and far-UV variation throughout the solar cycle. Combi et al. (2005) have pointed out that, in addition to providing an estimate for the water production rate, the spatial distribution of Lyα also provides information on the velocity distribution of the H daughter. In the analysis provided here, we neglect contributions to H production from sources other than water and its direct dissociation products.

In Figure 5, we show two profiles extracted from a 20 pixel (41′′25′′—two shutters wide) region centered on the brightest region of the P2minus detector and extending in the anti-Sun direction. The profile shown in black was acquired post-apogee
when the MSA was in a “partially opened” state and the count rate was not saturated. The jagged shape of the profile is due to closed shutters along the extraction direction. The profile shown in red was acquired pre-apogee when the MSA was in a “mostly opened” state but the count rate was saturated. The overall shape is less affected by closed shutters. The red profile has been shifted to match the core region of the unsaturated profile where the shutters are fully opened.

We have overplotted Lyα radial profiles for water production rates of \(8 \times 10^{29}\) and \(2 \times 10^{29}\) s\(^{-1}\), derived from steady-state Haser models modified to include compensation for saturated radial profiles that become optically thick toward the center of the coma. The higher rate is a reasonable match to the upper envelope of the core region at radii \(\lesssim 5 \times 10^4\) km, while the lower rate matches the upper envelope toward the outer regions at radii \(\gtrsim 10^5\) km. This is suggestive of an increasing water production rate in apparent agreement with that observed by Combi et al. (2014), who found \(Q_{\text{H,O}} = 3.8 \times 10^{29}\) s\(^{-1}\) on November 19.6, and \(19.4 \times 10^{29}\) on November 21.6, albeit from a large aperture observation. Our water production observation is most closely bracketed by those from Dello Russo et al. (2016), which were derived from the small aperture of IRTF/CSHELL on the nights of 2013 November 19 and 20.

Starting at November 19.71, they found a water production rate of \(Q_{\text{H,O}} = 2.4 \pm 0.1 \times 10^{29}\) s\(^{-1}\), which steadily increased to \(Q_{\text{H,O}} = 4.4 \pm 0.3 \times 10^{29}\) s\(^{-1}\) by 19.96 November. Between November 20.70 and 20.88, they found an average value of \(Q_{\text{H,O}} = 3.7 \pm 0.4 \times 10^{29}\) s\(^{-1}\).

All of these observations are well bracketed by the water production rates found by DiSanti et al. (2016) using IRTF/CSHELL. They quote \(Q_{\text{H,O}} = 1.6 \pm 0.1 \times 10^{29}\) s\(^{-1}\), \(4.3 \pm 0.3 \times 10^{29}\) s\(^{-1}\), \(9.9 \pm 0.5 \times 10^{29}\) s\(^{-1}\), and \(4.1 \pm 0.2 \times 10^{29}\) s\(^{-1}\) on November 18.7, 19.9, 22.7, and 23.0, respectively.

### 4.3. Carbon Production

In Figure 6, we show background-subtracted count rate images with linear scaling from the zero-order channel covering a \(332'' \times 332''\) region \((\pm 10^5\) km\(^2\). The zero-order imaging bandpass, ranging over \(\sim 1300\) to \(1800\) Å, is sensitive to the emission from a number of cometary species. The 1 au fluorescent efficiencies \((g\text{-factors})\) listed in Table 1 show that \(g\text{-factors} = 1\) for \(\lambda = 1657\) has the highest \(g\text{-factor}, followed by the band sum of CO, S I \(\lambda = 1475\), and O I \(\lambda = 1302\), respectively. Here, we present evidence in support of \(C I \lambda = 1657\) as the dominant source of emission in the zero-order images.
Figure 8. Zero-order count rate over \( \pm 10^3 \) km region centered on the nucleus in black histogram. The vertical dotted lines mark periods where the total number of open shutters changed in response to target acquisition and attempts to deploy preprogramed slits. The gray shaded regions mark times over which the images in Figures 6(a)–(d) were extracted. The atmospheric transmission at the wavelength of the C I \( \lambda 1657 \) emission is shown in blue. The atmospheric transmission for the CO bands is shown in red. The count rate at reentry is consistent with C I \( \lambda 1657 \) as the dominant emitting species in the zero-order channel. The dotted line at the bottom indicates the 1σ statistical error for the count rate.

Figure 9. Zero-order profile averaged over concentric circles surrounding the comet. The flux in this profile is dominated by emission from of C I \( \lambda 1657 \) as discussed in Section 4.3. Black is the profile acquired post-apogee. Red is the profile near reentry when the attenuation due to the atmosphere is strongest. Overplotted in blue is a vectorial model for the steady-state production of carbon from a parent molecule at the rate of 4 \( \times 10^5 \) s\(^{-1}\). The gray shaded regions mark times over which the images in Figures 6(a)–(d) were extracted. The atmospheric transmission at the wavelength of the C I \( \lambda 1657 \) emission is shown in blue. The atmospheric transmission for the CO bands is shown in red. The count rate at reentry is consistent with C I \( \lambda 1657 \) as the dominant emitting species in the zero-order channel. The dotted line at the bottom indicates the 1σ statistical error for the count rate.

Observations using the Cosmic Origins Spectrograph (COS) on the HST on 2013 November 01, when the heliocentric velocity was \(-42 \) km s\(^{-1}\), found a S I \( \lambda 1425 \) line that was \( \approx 5 \) times stronger than the S I \( \lambda 1475 \) and comparable in strength to C I \( \lambda 1657 \) (Weaver et al. 2014). However, as shown in Figure 4(c), the g-factor for S I \( \lambda 1425 \) has a strong dependence on heliocentric velocity, dropping by a factor of 3 at \(-62.7 \) km s\(^{-1}\), with respect to that at \(-42 \) km s\(^{-1}\), and is below that of S I \( \lambda 1475 \) (panel d). We further note that the COS aperture is only 2\( \times 5 \) in diameter, comparable to our pixel and much smaller than the extractions shown in Figure 6. Cometary sulfur emissions typically extend over a much narrower angular extent in comparison to carbon (e.g., McPhate et al. 1999), and so the C I \( \lambda 1657 \) intensity measured by COS samples only a small fraction of the flux available. We conclude that sulfur contributions in our zero-order image are likely to be \( \approx 10\% \) that of carbon. The band-integrated g-factor for CO is 1.4 times that of S I \( \lambda 1475 \) (Table 1), and like sulfur has a narrow angular distribution in comparison to carbon, and hence we expect it to be similarly weak.

Oxygen is a strong byproduct of water dissociation. However, its g-factor at \(-62.7 \) km s\(^{-1}\) is a factor of \( \approx 50 \) smaller than the carbon line. Moreover, the geocentric velocity of the comet is only \(-4.5 \) km s\(^{-1}\), which leads to strong attenuation of O I \( \lambda 1302 \) by atomic O in the thermosphere where slant column densities at the observation angle of 89° from zenith, range from \( 10^{19} \) to \( 10^{16} \) cm\(^{-2}\) at altitudes between 100 and 300 km.

We can further discriminate between carbon and other potential emitters in the zero-order images by monitoring the count rate as the telescope descends into Earth’s atmosphere. Molecular oxygen (\( \text{O}_2 \)) absorption has a strong dependence on wavelength, which will selectively attenuate cometary emissions from different atomic and molecular species at different rates on the downleg portion of the flight. We have modeled the expected attenuation as a function of time during the flight for C I \( \lambda 1657 \), O I \( \lambda 1302 \), and the CO A-X band. A summary of the components of this model is shown in Figures 7(a)–(d).

In Figure 7(a), we show the \( \text{O}_2 \) Schumann–Runge continuum absorption cross section in black. The g-factors at 1 au, multiplied by the zero-order effective area in Figure 2, are shown in red for the CO A-X-band transitions, in blue for C I \( \lambda 1657 \), and in green for O I \( \lambda 1302 \). The altitude of the telescope as a function of time is shown in Figure 7(b). In Figure 7(c), we show the slant column densities of \( \text{O}_2 \) and O as a function of altitude. In Figure 7(d), we show the transmission profiles from each emission source as a function of time.

In Figure 8, we show the zero-order count rate over \( \pm 10^3 \) km region centered on the nucleus in black. The vertical dotted lines mark times when total number of open shutters were changed in response to attempts to deploy a slit. The transmission curve as a function of time during the flight for C I \( \lambda 1657 \), O I \( \lambda 1302 \), and the CO A-X band. A summary of the components of this model is shown in Figures 7(a)–(d).

In Figure 7(a), we show the \( \text{O}_2 \) Schumann–Runge continuum absorption cross section in black. The g-factors at 1 au, multiplied by the zero-order effective area in Figure 2, are shown in red for the CO A-X-band transitions, in blue for C I \( \lambda 1657 \), and in green for O I \( \lambda 1302 \). The altitude of the telescope as a function of time is shown in Figure 7(b). In Figure 7(c), we show the slant column densities of \( \text{O}_2 \) and O as a function of altitude. In Figure 7(d), we show the transmission profiles from each emission source as a function of time.

In Figure 8, we show the zero-order count rate over \( \pm 10^3 \) km region centered on the nucleus in black. The vertical dotted lines mark times when total number of open shutters were changed in response to attempts to deploy a slit. The transmission curve as a function of time during the flight for C I \( \lambda 1657 \) is an excellent match to the count rate during the period of reentry. This is strong evidence for carbon as the dominant source of emission in these images. The lack of any sort of parabolically varying component in this rate is an indicator that O I \( \lambda 1302 \) is not present at a significant level.

In Figure 9, we plot as a black histogram the radial profile of the zero-order emission averaged over annuli centered on the pixel of peak brightness in the image acquired post-apogee (Figure 6(b)). The radial profile for the image acquired at the end of the downleg (Figure 6(d)) is plotted in red. The latter profile has a less pronounced peak. In Section 4.3.1, we will use the difference of these two profiles to constrain the CO production rate.

We overplot vectorial models representative of carbon as produced by a parent with 1 au lifetimes of \( 1.3 \times 10^6 \) and \( 5 \times 10^5 \) s as dashed and solid blue lines, respectively. The former lifetime is that expected from a CO parent. It clearly does not fit the observation. The latter lifetime provides a good fit to the observation, but leads to the conclusion that a parent molecule with a much short lifetime than CO is responsible for the C production. \( Q_C \approx 4 \times 10^{28} \) s\(^{-1}\), assuming a parent lifetime of \( 5 \times 10^4 \) s.
4.3.1. CO Production Constraint

Parent molecular species sublimating directly from the nucleus with optically thin column densities, like CO, are point sources as viewed by Earth bound telescopes, exhibiting a sharp peak at the center of an image. Our atmospheric transmission calculations, along with the zero-order count rate observation (Figure 8), indicate that the downleg image should be mostly devoid of CO emission and should contain only C I λ1657 emission, albeit somewhat attenuated. The difference between the profile acquired post-apogee (Figure 6(b)), which has C I λ1657 and possibly some CO at the center, and that acquired on the downleg (Figure 6(d)), which has only C I λ1657, allows us to place a limit on the level of CO production.

In Figure 10(a), we plot the zero-order image profile acquired post-apogee in black with the downleg profile in red. We have multiplied the downleg profile by a factor of 1.6 to account for atmospheric attenuation of C I λ1657, which provides a good match to the wing of the post-apogee profile at large radius. The difference between the two profiles is shown in blue. In Figure 10(b), we show, on a log–log plot, the differenced radial profile in black along with a simple Haser model in red for CO sublimating from the comet with a production rate of $Q_{\text{CO}} = 5^{+1.5}_{-1.2} \times 10^{28} \text{s}^{-1}$ with 1σ errors derived from photon statistics. This can only be considered an upper limit as the enhancement is slight and dominated by a single resolution element.

5. CONCLUSIONS

We find an Lyα radial profile that is not well matched by Haser models with steady-state water production. At small radii, the emission is consistent with a production rate of $Q_{\text{H}_2\text{O}} \sim 8 \times 10^{29} \text{s}^{-1}$, while at large radii the profile is better matched by a lower production rate of $\sim 2 \times 10^{29} \text{s}^{-1}$. This suggests that at the time of our observation, 2013 November 20.49, ISON was undergoing a strong increase in water production on linear scales of $10^3$ to $5 \times 10^3 \text{ km}$. The overall increase is in general agreement with the SWAN observations by Combi et al. (2014), and well bracketed by the DiSanti et al. (2016) and Dello Russo et al. (2016) water production determinations. However, it is somewhat at odds with the SWAN daily average, which shows a slight downward trend in the water production rate at the time of our observation. The SWAN daily average was calculated from a time-resolved model that accounts for the photodissociation kinetics and thermalization processes from various H parent species that effect the Lyα brightness profile on scales $\geq 1$. This dimension is significantly larger than our entire FOV of ($30^\circ$, $\sim 10^6 \text{ km}$), offering a potential explanation for the discrepancy and suggesting that our close-in look may offer insight into the dissociation processes during the disruption event.

The flux in the imaging channel is consistent with C I λ1657 emission. We find a carbon production rate of $\sim 4 \times 10^{28} \text{s}^{-1}$ with a parent lifetime of $\sim 5 \times 10^4 \text{s}$. This lifetime is shorter than expected from CO, implying that CO is not a dominant source of carbon in the coma. Lim et al. (2014) and Morgenthaler et al. (2011) came to similar conclusions regarding comets C/2001 Q4 (NEAT) and C/2004 Q2 (MACHHOLZ), although our lifetime is considerably shorter than that inferred for those two comets. Our production rate of carbon with respect to water is $C/\text{H}_2\text{O} \approx 5\%$.

We have taken advantage of the variable transmission to select far-UV wavelengths offered by molecular oxygen in the Earth’s atmosphere to constrain the production rate of CO sublimating from the surface of ISON to be $Q_{\text{CO}} \lesssim 5 \times 10^{28} \text{s}^{-1}$. The upper limit on the ratio of carbon monoxide to water is <6%. This upper limit is considerably larger than those derived from COS observations. They found $Q(\text{CO}) = 3 \times 10^{26} \text{s}^{-1}$ and $2.7 \times 10^{26} \text{s}^{-1}$ on October 22 and November 01, respectively, when the comet was at heliocentric distances of $\approx 1.2$ and $1.0\text{ au}$. (Weaver et al. 2014). Deconvolved daily averages of the water production rates derived from the SWAN Lyα imager (Combi et al. 2014) indicate $Q(\text{H}_2\text{O}) = 1.6 \times 10^{28} \text{s}^{-1}$ and $2.2 \times 10^{28} \text{s}^{-1}$ around these dates, suggestive of a gradual decrease in the CO/$\text{H}_2\text{O}$ ratios of 1.9% to 1.2%, in line with the non-steady evolution that characterized ISON’s ingress.

In future work, we intend to examine our data in the context of nearly contiguous far-UV spectral observations acquired over 2013 November 19 to 21 made by the Mercury Atmospheric and Surface Composition Spectrometer (MASC) on NASA’s MESSENGER spacecraft to further investigate the water production variability and to place more stringent limits on the CO production during this extremely volatile period.
The authors would like to acknowledge the sacrifices made by the personnel associated with the NASA Sounding Rocket Program Office, their Contractors, the Navy Launcher Team, and the Army Range Control at White Sands Missile Range, all of whom showed exemplary dedication in carrying out this time critical mission. We would also like to acknowledge the innumerable, essential, and critical contributions of our JHU project engineer, Russell Pelton, in providing support to this mission. Funding for this work was provided to the Johns Hopkins University through NASA sounding rocket grants No. NNX11AG54G and NNX14AI78G.

Facilities: Wallops Flight Facility, White Sands Missile Range.

REFERENCES

Bowen, I. S. 1947, PASP, 59, 196
Budzien, S. A., Festou, M. C., & Feldman, P. D. 1994, Icar, 107, 164
Combi, M. R., Fougere, N., Makinen, J. T. T., et al. 2014, ApJL, 788, L7
Combi, M. R., Makinen, J. T. T., Bertaux, J.-L., & Quemerais, E. 2005, Icar, 177, 228
Dello Russo, N., Vervack, R. J., Kawakita, H., et al. 2016, Icar, 266, 152
DiSanti, M. A., Bonev, B. P., Gibb, E. L., et al. 2016, ApJ, 820, 34
Fastie, W. G., & Kerr, D. E. 1975, ApOpt, 14, 2133
Festou, M. C. 1981, A&A, 95, 69
Fleming, B. T., McCandliss, S. R., Kaiser, M. E., et al. 2011, Proc. SPIE, 8145, 81450B
Fleming, B. T., McCandliss, S. R., Redwine, K., et al. 2013, Proc. SPIE, 8859, 88590Q
Greenstein, J. L. 1958, ApJ, 128, 106
Hasi, L. 1957, BSRSL, 43, 740
Li, M. J. e. a. 2005, Proc. SPIE, 5650, 9
Lim, Y.-M., Min, K.-W., Feldman, P. D., Han, W., & Edelstein, J. 2014, ApJ, 781, 80
McCandliss, S. R., Fleming, B., Kaiser, M. E., et al. 2010, Proc. SPIE, 7732, 1
McCandliss, S. R., France, K., Feldman, P. D., et al. 2004, Proc. SPIE, 5488, 709
McCandliss, S. R., Kruk, J. W., Blair, W. P., et al. 2008, Proc. SPIE, 7011, 701120
McPhate, J. B., Feldman, P. D., McCandliss, S. R., & Burgh, E. B. 1999, ApJ, 521, 920
Morgenthaler, J. P., Harris, W. M., Combi, M. R., Feldman, P. D., & Weaver, H. A. 2011, ApJ, 726, 8
Novski, V., Novichonok, A., Burhonov, O., et al. 2012, CBET, 3238, 1
Oort, J. H. 1950, BAN, 11, 91
Oort, J. H., & Schmidt, M. 1951, BAN, 11, 259
Sekanina, Z., & Kracht, R. 2014, arXiv:1404.5968
Swings, P. 1941, LiCOb, 19, 131
Weaver, H., A'Hearn, M., Feldman, P., et al. 2014, in Asteroids, Comets, Meteors, Ultraviolet spectroscopy of comet ISON (2012 S1), ed. K. Muinonen et al., 583
Whipple, F. L. 1950, ApJ, 111, 375
Whipple, F. L. 1951, ApJ, 113, 464
Whipple, F. L. 1978, M&F, 18, 343