The Evolving Coma Morphology of Interstellar Comet 2I/Borisov with Deep HST Imaging

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ABSTRACT

We present high resolution, deep imaging of interstellar comet 2I/Borisov taken with the Hubble Space Telescope/Wide Field Camera 3 on 2019 October 12, November 16, December 9, 23-25 UTC (Jewitt et al. 2019a; Meech et al. 2019). Deep image stacks of 2I on all dates reveal no discernible signal from a nucleus suggesting that the coma is a strong component of 2I’s total sunlight scattering cross-section. We locate a possible jet-like structure near the optocenter of 2I 1-2” or 2,000 - 3,000 km in length that appears to change positions independent of the orbital velocity and anti-solar vectors over the four observation dates indicating possible rotational variation of the morphology but does not show short term variability during the ∼14 orbit, ∼70 h duration of the observations on 2019 December 23-25 UTC. Using the 14 orbit dataset from 2019 December 23-25, we see slight, ≲0.05 magnitude variation in the brightness of the lightcurve corresponding to a possible double-peaked period of ∼11 h, though the small amplitude variation could be due to short-term changes in the activity of 2I. In addition, we use deep image stacks from the highest spatial resolution observations to estimate a ∼1-2 km diameter consistent with previous high-resolution ground-based observations (Bolin et al. 2019).

Key words: minor planets, comets: individual (2I/Borisov) – galaxy: local interstellar matter

1 INTRODUCTION

The second interstellar object, 2I/Borisov (2I), has been shown to have a cometary appearance similar to other Solar System comets at heliocentric distances ∼3 au (Guzik et al. 2019; Bolin et al. 2019), as well as containing CN gas, a common volatile species among Solar System comets (Fitzsimmons et al. 2019) and H$_2$O tracer molecules (McKay et al. 2019; Crovisier et al. 2019). In addition, somewhat similar to Solar System Jupiter Family Comets is the apparent depletion of C$_2$ gas in the coma of 2I (A’Hearn et al. 1995; Kareta et al. 2019; Opitom et al. 2019). The color and activity of 2I have been revealed to be similar to Solar System comets. The visible to near-infrared photometry and spectra of the comet are reddish to neutral suggesting the presence of refractory organics and water-ice common in comets (de León et al. 2019; Bolin et al. 2019). Additionally, the activity has been revealed by its long-term lightcurve trend to be driven by super-volatiles such as CO/CO$_2$ as indicated by the long-term brightness trend from serendipitous pre-discovery observations by the Zwicky Transient Facility (ZTF) with the addition of H$_2$O-driven activity as the comet approaches the Sun (Bolin et al. 2019; Ye et al. 2019). Other possible drivers of the distant activity may include annealing of amorphous water-ice (Sekanina 2019), but in any case, it seems that the activity of 2I is similar to that of Solar System comets.

Constraints on the size from gas production rates (Fitzsimmons et al. 2019), statistical arguments (Jewitt & Luu 2019) and high-resolution adaptive optics imaging from ground-based facilities (Bolin et al. 2019) suggest indicate that ∼ km-scale diameter. However, direct detection of the nucleus has not yet been possible due to the flatness of the coma profile (Jewitt & Luu 2019). In addition, fine structures such as jets from the emission of cometary gases have not yet been observed in part due to the limits on the spatial resolution when observing from the ground at the >2 au geocentric distance of the comet. Here, we present high-resolution and deep stack optical observations made with the Hubble Space Telescope to study the coma structure of 2I.
2 OBSERVATIONS

Hubble Space Telescope (HST) was used to observe 2I with director’s discretionary time on 2019 October 12 UTC (Jewitt et al. 2019a). Up to seven orbits were awarded for the director’s discretionary time, but four orbits were used on 2019 October 12 UTC to observe 2I. During each orbit on 2019 October 12, six 260 s F350LP filter exposures were obtained with the 2K subarray of the WFC3/UVIS camera (Dressel 2012) for a total of 24 exposures and 6240 s integration time. The F350LP filter has a central wavelength of 581.95 nm with a FWHM bandpass of 489.26 nm (Deustua et al. 2017). The comet was observed on four back-to-back orbits and was tracked non-sidereally at its rate of sky motion.

Additional observations of 2I were conducted with one orbit of HST on 2019 November 16 UTC and on 2019 December 9 UTC. On both of these dates, six 230 s exposures were taken of 2I with the F350LP filter tracking on its rate of motion. Only four of the 230 s exposures were used from November 16 UTC because the coma of 2I significantly overlapped with an extended background galaxy in two of the 230 s exposures resulting in a total exposure time of 920 s. All six exposures taken on 2019 December 6 were used resulting in a total exposure time of 1380 s.

A fourth set of observations of 2I were obtained with HST (Meech et al. 2019) that consisted of 14 orbits spread out over a ∼ 70 h period between 2019 December 23 01:54:45 and 2019 December 25 21:24:46 UTC. Observations during each of the 14 orbits on 2019 December 23–25 consisted of five 380 s exposures using the F350LP filter providing a total of 1900 s integration time per orbit. The viewing geometry of 2I during all of the HST observations described here are available in Table 1.

3 RESULTS

The 24 F350LP images obtained on 2019 October 12 were aligned and median stacked into a single composite image equivalent to a total integration time of 6240 s. Cosmic ray removal was done within the vicinity of the comet detection by interpolating the regions of the chip affected by cosmic rays by the average values of the regions surrounding the cosmic ray strikes. A composite image of the comet with the radial profile of the coma removed is seen in the first panel of Fig. 1. At the time of the HST observations on 2019 October 12 UTC, 2I had a heliocentric distance of 2.38 au, a geocentric distance of 2.79 au, a phase angle of 20.26° and an orbital plane angle of −13.53°. A clear tail is present in excess of 30″, similarly seen in the ground-based observations (Jewitt & Luu 2019; Bolin et al. 2019), with a position angle opposite of the orbital velocity indicating the presence of large, micron-sized dust grains. However, the position angle of the tail may also be compatible with moving in the anti-solar direction which is difficult to distinguish due to projection effects at the modest orbital plane angle between HST and the comet at the time of the observations.

Contours showing the structure of the tail are overplotted on the radial profile removed composite image showing an enhancement in surface brightness of the coma near its center as seen in the center panel of Fig. 1. A smoothed version of the radial profile removed image is shown in the third panel revealing an azimuthally non-symmetric surface brightness profile within 5″ of the center of the coma at position angles 0° and 180°. The thin southern surface brightness enhancement at a position angle of ∼180°, more easily seen in the bottom panel image of Fig. 1 that has been smoothed with a Gaussian filter to enhance low surface brightness features, may be interpreted as a localized jet, possibly consisting of the CN gas detected by Fitzsimmons et al. (2019) as seen in some Solar System comets (Knight & Schleicher 2013; Bodewits et al. 2018).

The F350LP data from 2019 November 16 UTC and 2019 December 9 UTC are also median stacked with a total equivalent exposure time of 920 s and 1380 s respectively and with the coma’s radial profile removed as seen in the top panels of Fig. 1. Similarly, a fine jet structure appears in both the 2019 November 16 UTC 2019 December 9 UTC data with a position angle of ∼90° and ∼60° respectively as seen in the center and bottom panels of Fig. 1. A fourth dataset was used consisting of 14 orbits of F350LP data taken on 2019 December 23–25 UTC. A mosaic showing the radial profile-removed coma centered on the optocenter is shown in Fig. 2. A jet-like structure with a position angle of ∼60°, similar to what is seen in the 2019 December 9 UTC data. The jet does not appear to significantly change its position angle even though the time span of the observations is ∼70 h. A signal from the nucleus was not seen in the radial profile of the 2I detections in the median stacks from all four datasets.

We calibrate the photometry on 2019 October 12 according to the aperture correction and zero-points determined for the F350LP filter (Deustua et al. 2017) and measure the photometry of 2I in the HST images using a circular aperture with an equivalent 10,000 km aperture resulting in $m_{F350LP} = 17.43 ± 0.01$. Ground-based $V$ filter observations of 2I by the MLO 1.0-m were conducted near simultaneously to the HST observations on 2019 October 12 UTC with the comet’s $V = 17.55 ± 0.04$ (Bolin et al. 2019) which we used to roughly estimate the color between the F350LP and the $V$ filters, $F350LP - V = -0.12 ± 0.04$.

We then use the F350LP - $V$ band color to determine the $V$ magnitude in the 2019 October 12 observations using an aperture size of 0.2″ and a sky subtraction annulus between 0.2–0.8″ resulting in a $V$ magnitude of 21.11 ± 0.04. The smaller 0.2″ aperture enabled by HST allows for the removal of orders of magnitude more light from the coma within the vicinity of the nucleus compared to ground-based observations enhancing the contrast between the coma nucleus (e.g. Jewitt et al. 2019b). We apply the same technique to the 2019 November 16 UTC and 2019 December 9 UTC data resulting in $V$ magnitude measurements of 20.73 ± 0.04 and 20.67 ± 0.04 respectively.

Using the following equation and the $V$ magnitudes calculated above

$$H = V - 5 \log_{10}(r_{h}\Delta) - \Phi(\alpha)$$ (1)

we calculate the absolute magnitude $H$ according to the heliocentric distance $r_{h}$ and geocentric distance $\Delta$ from Table 1 and $\Phi(\alpha) = 0.04\alpha$ resulting in $H$ magnitudes of 16.18 ± 0.04, 16.37 ± 0.04 and 16.52 ± 0.04. The apparent decrease in $H$ magnitude is a projection effect due to using a fixed angular size for the aperture used in the photometric measurements as the comet approaches the Earth. We also note...
that the errors on the H magnitudes may be underestimated in part due to the unknown phase function of 2I.

3.1 Lightcurve and Morphological evolution

Due to the density and slow crossing time of dust within 2I’s coma, measuring any short term lightcurve variations on the order of hours to 10’s of hours caused by the rotation of the comet’s nucleus is difficult at the coarse resolution of ground-based observations (Jewitt & Luu 2019). We search for short-term variations in the lightcurve such as due to the rotation of the nucleus using the high-resolution WFC3/UVIS taken on 2019 October 12 UTC and in the data taken on 2019 December 23-25 UTC. As discussed in Jewitt (1991), dilution of light from the nucleus by dust in the coma can dampen the variability in a comet lightcurve for timescales shorter than the crossing time of dust within the scale of the photometric aperture. At distances close to the surface of the comet, the speed of dust coupled to gas is approximately the speed of sound in gas (Gerig et al. 2018), 0.43 km/s at the black body temperature of the gas, 181 K, at the heliocentric distance of the comet of 2.79 au on 2019 October 12 UTC and 197 K at the heliocentric distance of the comet of 2.03 au on 2019 December 24 UTC. For ground-based observations taken with a 10,000 km aperture, the dust crossing time is ∼6.5 h. We can use the superb 0.04″ resolution of the WFC3/UVIS data to measure the brightness of the comet with a smaller aperture enabling shorter coma dust dampening timescales.

We use a 0.2″ aperture centered on the peak of the comet’s brightness profile with a contiguous sky-subtraction aperture 0.2″-0.8″. The equivalent distance spanning 0.2″ at a distance of 2.79 au, the geocentric distance of the comet on 2019 October 12 UTC, is ∼400 km in which the crossing time of dust is ∼0.3 h, and ∼300 km at the geocentric distance of the comet of 1.93 au on 2019 December 24 2019 UTC corresponding to a crossing time of ∼0.2 h. In addition, as discussed above, the smaller 0.2″ aperture enhances the contrast between the region containing the nucleus of the comet and the rest of the coma enhancing the potential for measuring the variability of the lightcurve from the rotation of the comet’s nucleus (e.g., Lamy et al. 1998a,b). Although there is the lack of a nucleus signal in the composite stacks as discussed above, a large, >2 magnitude lightcurve amplitude such as seen for 1I/Oumuamua (Meech et al. 2017; Bolin et al. 2018) could potentially enhance the nucleus signal for 2I and make its detection possible through the coma if it is near the brighter part of its rotation phase.

Our HST photometric measurements of 2I from HST observations taken on 2019 October 12 are presented in the first panel of Fig. 3. The time of the observations has been corrected for light-travel time and the photometry has been kept in F350LP magnitude. The lightcurve is flat with no 0.01-0.02 magnitude uncertainty, (4) heliocentric distance, (5) geocentric distance, (6) phase angle, (7) Earth and target orbital plane angle. Due to the density and slow crossing time of dust within 2I’s coma, measuring any short term lightcurve variations on the order of hours to 10’s of hours caused by the rotation of the nucleus is difficult at the coarse resolution of ground-based observations (Jewitt & Luu 2019).
The radial profile of the coma has been removed from the detection of 2I in each median stack. The cardinal direction vectors, the solar and orbital velocity and spatial scale are indicated.

in the double-peaked lightcurve period vs. spectral power curve is located at 10.7 h with a formal significance of \( p \approx 10^{-6} \), though we caution that this inference of the rotation period may be suspect since the phased data as seen in the third panel indicate a small amplitude of only \( \sim 0.05 \) magnitudes, comparable to within a factor of a few of the errors on the individual data points. Although, a small lightcurve amplitude might be expected in this case where the nucleus was not detected in the coma of this object (Bolin et al. 2019; Jewitt et al. 2019a) implying a source dominated by the coma’s dust (e.g., Hsieh et al. 2012). We further caution that the limited 70 h data set showing this possible periodicity may be contaminated by observations of short-term changes in the activity of 2I at the relatively high spatial resolution allowed by \( HST \) which have been shown in the case of 67P/Churyumov-Gerasimenko to occur on the time scale of \( \sim 0.5 \) h or less, comparable to the crossing time of dust within the 0.2" aperture used to measure the photometry of the lightcurve (Lin et al. 2017). We note that the apparent lack of or at least very small, \( \sim 0.05 \) magnitude lightcurve variation, seen in this work on relatively short time scales spanning a few days and also in longer time scales spanning weeks, (Gladman et al. 2019), is in contrast with the first interstellar object, 1I/‘Oumuamua which was observed to have \( >2 \) magnitude variations in its lightcurve (Knight et al. 2017; Bolin et al. 2018). This implies that the coma of 2I may be too compact to see the rotational variation of the nucleus (Hsieh et al. 2012), or that the nucleus itself is spherical, has slow rotation period or is oriented an unfavorable geometry for observing the rotational variation in its lightcurve (e.g., Hanuš et al. 2018). The appearance of the jet feature as seen in Fig. 1 on 2019 October 12 UTC and 2019 December 23-25 as seen in Fig. 2 seems to stay stationary, possibly supporting slow rotation period, or that the motion of the jet is not observable due to the limitations of the resolution of \( HST \).

### 3.2 Diameter Estimate

An upper limit to the size of 2I of 1-2 km was inferred by measuring the effective cross-section using high-resolution data from ground-based adaptive optics observations using
the Keck Telescope OSIRIS instrument during 2019 October 4 UTC (Bolin et al. 2019). We use the high-resolution observations from HST taken on December 25 2019 UTC to estimate an upper limit of the size of 2I (e.g., Lamy et al. 2004) when it was on its closest approach to the Earth enabling a size measurement at higher spatial resolution than in the adaptive optics observations of 2I taken on 2019 October 4 UTC. The geocentric distance of 2I on 2019 December 25 UTC was ~1.93 au providing only ~ 300 km coverage in the 0.2” aperture centered on the peak central brightness used to measure the H of the comet.

We translate the $H$ magnitude, equal to 16.64, computed from Eq. 1 using the 0.2” aperture with the detection of 2I from the median stack of the data taken on 2019 December 25 UTC into an effective cross-section, $C$, in units of km$^2$ using the following formula

$$C = 1.5 \times 10^6 \rho_v^{-1} 10^{-0.4H}$$

from Jewitt & Meech (1986), where $\rho_v$ is the albedo of the comet, assumed to be 0.1, typical for comet dust (Kokolopoulou et al. 2004) resulting in a cross section of 3.31 ± 0.13 km$^2$. We then use $D = 2\sqrt{C/\pi}$ to calculate the diameter from $C$, obtaining the values 2.05 ± 0.04 km. We refine this measurement of the diameter using the non-detection of a nucleus in the deep image stack from 2019 December 25 by assuming a 2 $\sigma$ upper limit from the noise level after subtracting the flux of the coma corresponding to $\leq$10% of the central PSF flux (Bauer et al. 2017; Hui & Li 2018), we find an upper limit to Borisov diameter of $\leq$1.0 km. A similar estimate was found with HST and Keck OSIRIS adaptive optics data from 2019 October UTC when the comet was ~2.8 au from the Sun (Jewitt et al. 2019a). Our nucleus diameter estimate implies a mass of $\sim$10$^{12}$ kg assuming a comet nucleus density of 400 kg/m$^3$ (e.g., Pätzold et al. 2016), typical sizes for Solar System comets in the km size range (Fernández et al. 2013; Bauer et al. 2017; Boe et al. 2019).

4 CONCLUSIONS

Although many observations of 2I have already occurred (e.g., Jewitt & Luu 2019; Fitzsimmons et al. 2019; Bolin et al. 2019), our understanding of this object and its context within the greater interstellar comet populations is only beginning to unfold. Even at the best spatial scales, determining the true size of 2I remains elusive due to its possible small size and the presence of dust in the light-scattering cross-section of the nuclear PSF similar to comets with optically thick coma (e.g., Lisse et al. 1997). Determining the true size of 2I may require waiting for its activity to decrease as it leaves the Solar System in the next couple of years with advanced assets such as the James Webb Space Telescope or the Atacama Large Millimeter Array.

Additionally, understanding its rotational properties and inferring its shape properties may prove equally difficult as determining its nucleus size since the nucleus may be either too small to observe through the dust and observe any rotational variations. Determining its rotational state may rely on observing the movement of the morphology of fine structures at high resolutions and sensitivities such as the jets presented in this work combined with dynamical models of its dust (??). This may be possible with additional high-resolution imaging from HST or ground-based adaptive optics, or by using comet filters that are sensitive to the comet gases that may consist of these jets (Knight & Schleicher 2013; Bodewits et al. 2018). In any case, it appears as though 2I may be rotating may be slowly $>10$ h, which is not atypical for solar system comets (Samarasinha et al. 2004; Kokotanekova et al. 2017).

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