

Pre-discovery Activity of New Interstellar Comet 2I/Borisov Beyond 5 AU

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ABSTRACT

Comet 2I/Borisov, the first unambiguous interstellar comet ever found, was discovered at ~ 3 au from the Sun on its inbound leg. No pre-discovery detection beyond 3 au has yet been reported, mostly due to the comet's proximity to the Sun as seen from the Earth. Here we present a search for pre-discovery detections of comet Borisov using images taken by the Catalina Sky Survey (CSS), Pan-STARRS and Zwicky Transient Facility (ZTF), with a further comprehensive follow-up campaign being presented in Bolin et al. (2019). We identified comet Borisov in ZTF images taken in May 2019 and use these data to update its orbit. This allowed us to identify the comet in images acquired as far back as December 2018, when it was ~ 8 au from the Sun. This suggests that the activity of the comet is driven by a more volatile species other than H₂O, such as CO or CO₂. The comet was not detected in November 2018 when it was 8.5 au from the Sun, possibly implying an onset of activity around this time. We derive the radius of the nucleus to be < 7 km using the non-detection in November 2018, and estimate an area of ~ 0.5 – 10 km² has been active between December 2018 and September 2019, though this number is model-dependent and is highly uncertain. The behavior of comet Borisov during its inbound leg is observationally consistent with dynamically new comets observed in our solar system, suggesting some similarities between the two.

Keywords: comets: individual (2I/Borisov)

1. INTRODUCTION

Comet 2I/Borisov¹ (2I for short), discovered by G. Borisov at the Crimean Astrophysical Observatory on 2019 August 30, is the second interstellar object and the first unambiguous interstellar comet ever found. Early observations of 2I have revealed a sizeable coma (de León et al. 2019; Guzik et al. 2019; Jewitt & Luu 2019) and the detection of the emission from CN, C₂, and atomic oxygen (Fitzsimmons et al. 2019; Opitom et al. 2019; McKay et al. 2019). This

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¹ Formerly designated as C/2019 Q4 (Borisov). See Minor Planet Electronic Circular (MPEC) 2019-R106 and MPEC 2019-S72.

makes it distinctively different from the first discovered interstellar object 1I/‘Oumuamua, which did not exhibit a detectable cometary feature such as a coma and/or a tail (Meech et al. 2017; Ye et al. 2017; ‘Oumuamua ISSI Team et al. 2019). The detection of activity is important as it provides a way to probe the composition of the nucleus, which can be done through a direct analysis of gases in the coma, and by observing how the activity responds to different levels of insolation at different heliocentric distances.

2I was discovered at a heliocentric distance $r_H = 2.98$ au, with a brightness ($V = 18$ mag) that is well within the reach of modern near-Earth object (NEO) surveys. The belated discovery is primarily due to the fact that the comet was within 45° from the Sun, within the typical solar avoidance zone for ground-based optical telescopes, from early May to early September 2019.

A detection (or non-detection) at $r_H \gg 3$ au would better constrain the size of the nucleus (as the comet is likely less active) as well as its inbound orbit, and would be diagnostic of the comet’s volatile composition (Fitzsimmons et al. 2019), since the activity of most known (i.e., solar system) comets within ~ 3 –5 au is driven by water ice sublimation (e.g., Meech & Svoren 2004). All-sky, time-domain surveys allow for serendipitous observations of objects before they are discovered. Here we present a search for pre-discovery detections of 2I in the data of several sky surveys. We will describe the search process in § 2, the procedure of photometric analysis in § 3, and will then discuss the implication of the detections and non-detections in § 4 and § 5.

2. PRE-DISCOVERY DETECTIONS

2.1. Zwicky Transient Facility

The Zwicky Transient Facility (ZTF) is a wide-field optical survey utilizing the 1.2 m Palomar Oschin Schmidt and a dedicated camera with 55 deg^2 field-of-view (Bellm et al. 2019; Graham et al. 2019; Masci et al. 2019). Apart from two baseline surveys and a number of mini-surveys, ZTF executes a mini-survey (“Twilight Survey”) that observes regions with solar elongation down to 35° (Ye et al. in prep), which is particularly suitable for the search of pre-discovery detections of 2I. The first phase of the ZTF Twilight Survey was executed from November 2018 to June 2019, fortuitously covering the period before 2I reached solar conjunction in July 2019.

By using the ZChecker comet monitoring package (Kelley et al. 2019) and JPL orbit solution #12 (the most recent JPL solution at the time that the search was conducted), we identified a total of 202 images from 2018 October 1 to the discovery date of 2I (2019 August 30) that potentially contained the comet. All images use 30 s exposure times, and were taken in a wide range of observing circumstances, with 5σ limiting magnitudes between 16–21 and seeing between $1''$ – $5''$. The comet reached solar conjunction in July of 2019, and the last three sets of images acquired before that were taken in the course of the Twilight Survey on 2019 April 29, May 2 and May 5 respectively, when 2I was at $r_H = 5.20$ – 5.09 au and before reaching solar conjunction in July. Prior to these Twilight Survey data, the last image was taken on 2019 April 16, when the comet was at $r_H = 5.45$ au. The April 29 and May 5 observations were not optimal because only a few images were acquired, high sky background, and/or the comet being near image edges. The May 2 observations were particularly fortuitous as the comet was located in an overlapping strip between two fields, and thus have $2\times$ more images than we typically have (8 images total, instead of the typical 4 images per field). Therefore, we focused on the 2019 May 2 data for our initial search of a pre-discovery detection.

The astrometric observations available up to this point did not provide meaningful constraints on the cometary non-gravitational perturbations (e.g., Yeomans et al. 2004), which lead to different orbit solutions. To capture the ephemeris variations using different model assumptions, we fit the available astrometry as of 2019 October 3 using a gravity-only model, and two non-gravitational models that either assumed sublimation of H_2O (Marsden et al. 1973) or CO (Yabushita 1996) to be the primary driver of comet activity. We then combined all 8 images from May 2 following the apparent motion of 2I. The three solutions are tabulated in Table 1 (together with the final orbit, after we have successfully identified the comet in the ZTF pre-discovery data, as we discuss below), and the combined image as well as the uncertainty ellipses of the three solutions are shown as Figure 1. Because of the short arc and the low elongation of many of the astrometric positions, we note that the estimated non-gravitational parameters could be unreliable. In particular, the parameters for the H_2O -driven model appear to be too large to be credible, and are possibly caused by astrometric biases at such a small solar elongation.

We identified a possible detection at a signal-to-noise ratio (S/N) of ~ 10 on the combined May 2 image (Figure 2). The detection is within the 3σ uncertainty ellipses of gravity-only and CO non-gravitational solutions, and about $5''$ southeast of the predicted Minor Planet Center (MPC) position. Visually, the object is about $\sim 5''$ in diameter and is

Table 1. Orbital elements of various solutions in Figure 1, as well as the final solution (JPL 23), which uses precovery data and a CO-driven non-gravitational forces.

Parameter	Gravity-only	Nongrav – H ₂ O	Nongrav – CO	Final – CO
Pre-discovery detection used?	No	No	No	Yes
Epoch (TDB)	2019 Sep 16.0	2019 Sep 16.0	2019 Sep 16.0	2019 Sep 25.0
Perihelion time (TDB)	2019 Dec 8.65 ± 0.07 d	2019 Dec 13 ± 1 d	2019 Dec 9.1 ± 0.4 d	2019 Dec 8.5557 ± 0.0008 d
Perihelion distance q (au)	2.003 ± 0.003	1.85 ± 0.05	1.98 ± 0.02	2.00657 ± 0.00003
Eccentricity e	3.34 ± 0.01	2.7 ± 0.2	3.27 ± 0.07	3.3566 ± 0.0001
Inclination i	44.08° ± 0.03°	45.6° ± 0.5°	44.3° ± 0.2°	44.0513° ± 0.0003
Long. Ascending Node Ω	308.12° ± 0.03°	306.7° ± 0.4°	308.0° ± 0.2°	308.1484° ± 0.0002°
Argument of Perihelion ω	209.21° ± 0.06°	213° ± 1°	209.7° ± 0.5°	209.1247° ± 0.0008°
Radial accel. A_1 (au day ⁻²)	-	(3.5 ± 0.7) × 10 ⁻⁴	(1.4 ± 1.5) × 10 ⁻⁵	-
Transverse accel. A_2 (au day ⁻²)	-	(-2.7 ± 0.3) × 10 ⁻⁴	(-6.2 ± 5.6) × 10 ⁻⁶	(2.6 ± 0.5) × 10 ⁻⁷

Table 2. Summary of all the pre-discovery observations. The heliocentric and the geocentric distances of the comet (r_H and Δ) are given at the median time of the image epochs. FWHM is the average full-width-half-maximum of the image.

Images date	Median date (UT)	Survey	r_H (au)	Δ (au)	Images used	FWHM	Res.	r mag
2018 Oct 31 – 2018 Nov 21	2018 Nov 8.82	ZTF	8.55	7.90	g : 12; r : 16	1.4''–3.0''	-	$m_{3\sigma} > 22.69$
2018 Dec 13 – 2018 Dec 22	2018 Dec 19.15	ZTF	7.75	6.99	g : 6; r : 6	1.9''–2.7''	0.7''	21.19 ± 0.15
2019 Jan 17	2019 Jan 17.30	PS1	7.18	6.58	i : 4	0.9''–1.1''	-	
2019 Feb 24 – 2019 Feb 26	2019 Feb 25.18	ZTF	6.42	6.26	g : 3; r : 4	1.6''–3.6''	0.6''	20.97 ± 0.18
2019 Mar 1	2019 Mar. 1.10	CSS	6.35	6.24	Clear: 4	~ 3''	1.1''	~ 21
2019 Mar 16 – 2019 Mar 18	2019 Mar 17.18	ZTF	6.02	6.14	g : 4; r : 5	2.1''–2.9''	1.5''	20.46 ± 0.16
2019 Apr 9 – 2019 Apr 13	2019 Apr 12.16	ZTF	5.53	5.97	g : 3; r : 3	1.6''–3.0''	1.4''	20.42 ± 0.09
2019 May 2	2019 May 2.16	ZTF	5.15	5.79	r : 8	2.0''–2.1''	1.1''	20.12 ± 0.11
2019 May 5	2019 May 5.15	ZTF	5.09	5.76	r : 4	1.8''–2.5''	0.7''	20.16 ± 0.21

largely circular in shape, with no apparent sign of a tail. The object is barely visible on individual frames (Figure 2), with a motion consistent with that of 2I.

We then examined other images in the time period in question, using the same shift-and-stack technique as outlined above. The detection on 2019 May 2, if real, would have greatly reduced the ephemeris uncertainty from a few arcminutes to a few arcseconds back to January 2019, and would enable more pre-discovery data to be found. Since the comet is extremely faint, in order to eliminate contamination due to variable sky conditions and passing background stars, we only use frames that have (1) 5σ limit of $r \gtrsim 19.5$, (2) average full-width-half-maximum (FWHM) of < 3 pixels, and (3) have no background stars that are within $10''$ from the predicted position of the comet.

All the pre-discovery detections and non-detections are summarized in Table 2. We were able to trace the object back to 2018 December 13. Apart from the 2019 May 2 data, the object is not visible in individual frames, and a clear detection usually requires stacking images from multiple nights. By including these astrometric positions² with the post-discovery astrometric measurements of 2I and considering the non-gravitational effect, we were able to get a satisfactory orbital fit with residuals of order $1''$, which is slightly above the average compared to typical ZTF astrometries (better than $0.5''$). This is due to a weak systematic bias in the data, which is possibly caused by the fact that most astrometric data were taken at low solar elongation and therefore at high airmass, introducing some differential color refraction (DCR) bias (see also the discussion in § 4.4). Nevertheless, we identify the object observed from 2018 December to 2019 May 5 as 2I.

² Published in MPEC 2019-V34.

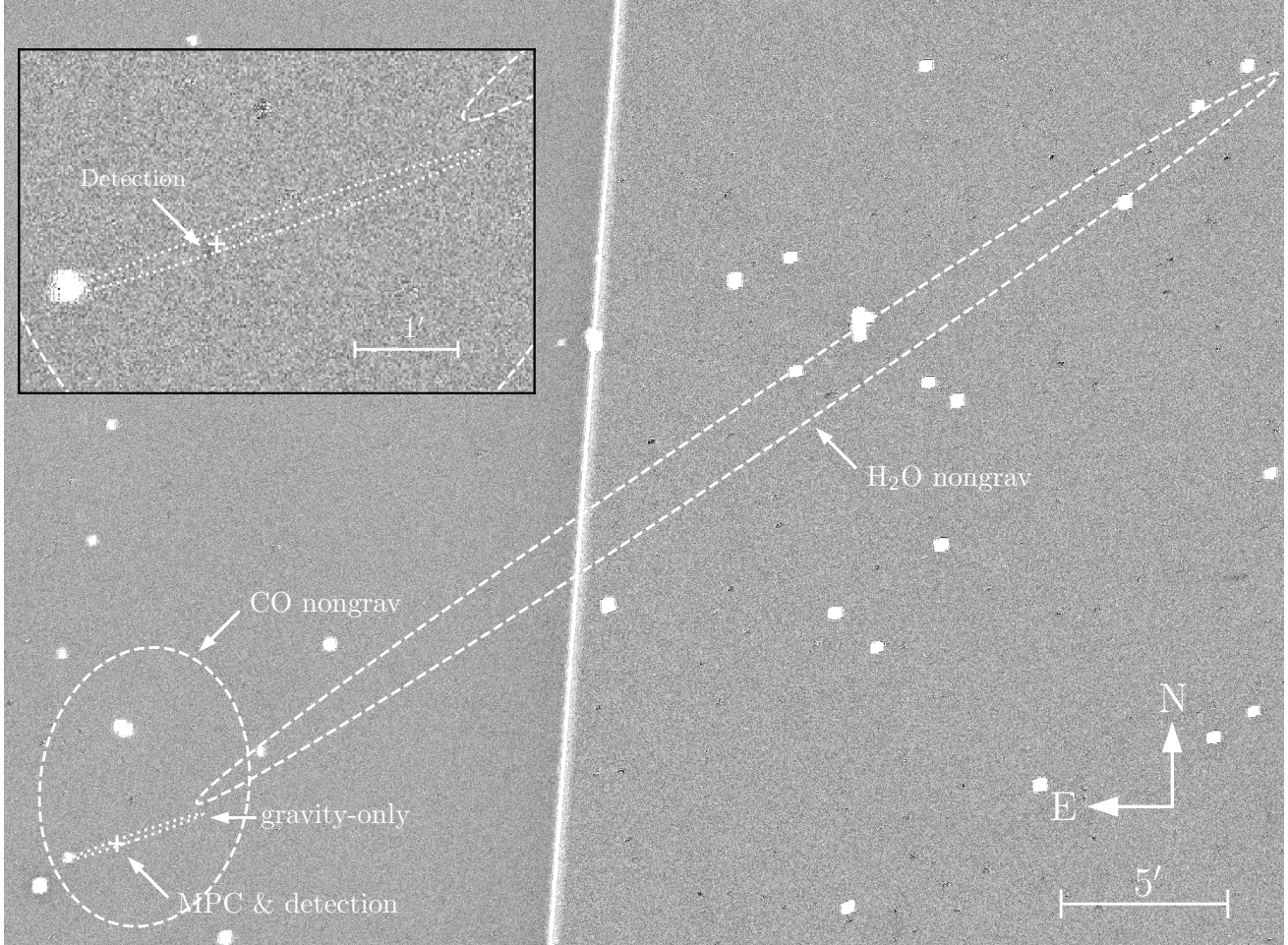


Figure 1. Combined image stacked following the predicted motion of 2I, using 8 images taken on 2019 May 2, with the pre-discovery detection of the comet marked. The MPC position is calculated using the orbit published in [MPEC 2019-T44](#). The motion rate difference between different orbit solutions is smaller than $1/5$ th of a pixel over the entire imaging session and is negligible. The input images have been subtracted with the reference images to remove background stars (i.e. “differenced” images, see [Masci et al. 2019](#)). The white blobs are masked stars. The image is plotted in inverted linear scale (i.e. sky is white, the comet is dark).

A point worth addressing is the non-detection in November 2018. The 3σ uncertainty of the position is $\sim 4''$ (4 pixels) along the major axis, and the motion rate difference between different orbit solutions is less than $1/4$ th of a pixel over the entire time span, but no comet is detected in the stack (Figure 3). Subsequent light-curve analysis (see § 4.1) shows that 2I should be ~ 1 mag above than the 3σ limit of the stack.

2.2. Pan-STARRS

The Pan-STARRS survey ([Chambers et al. 2016](#)) is a wide-field asteroid survey comprised of two identical 1.8 m telescopes, the Pan-STARRS1 (PS1) and Pan-STARRS2 (PS2). The survey has an image archive extending back to 2010. Using the ZTF precovery data along with the available astrometry from the Minor Planet Center up to 2019 October 1, we generate an ephemeris covering the period from 2018 January 1 (when 2I was well below any practical ground based telescope sensitivity) until the discovery date of 2019 August 30. Four 45 second *i*-band images taken by

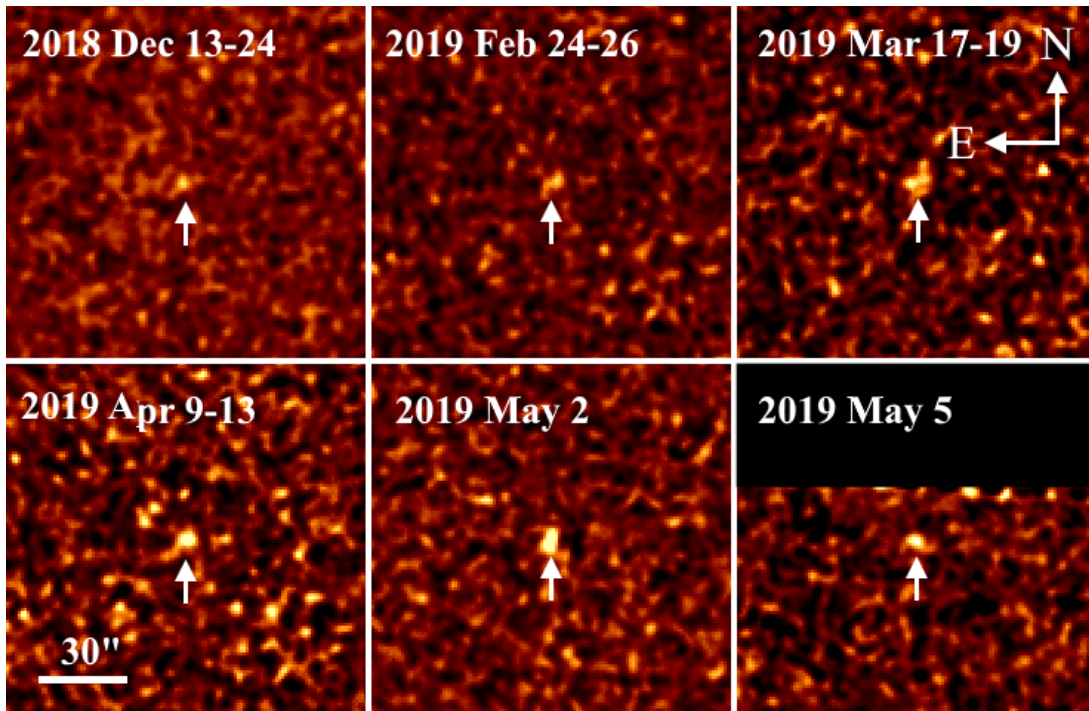


Figure 2. A close-up view of the pre-discovery detection of 2I in ZTF data. To improve the clarity, the stamps have been smoothed by a moving Gaussian function with a width of 7 pix at 1.5σ . The stamps are plotted in hyperbolic sine scale.

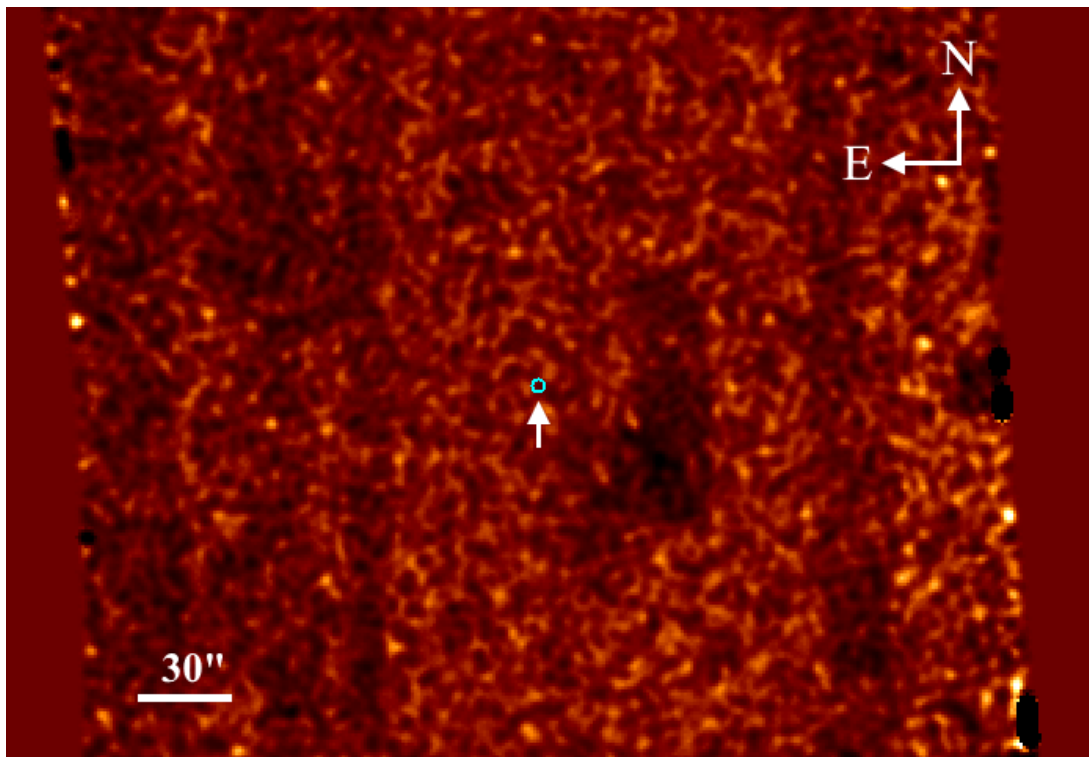


Figure 3. A close-up view of the ZTF non-detection image of 2I in November 2018. The image is smoothed by a moving Gaussian function with a width of 7 pix at 1.5σ and is plotted in hyperbolic sine scale. The circle in cyan marks the nominal of the comet and the size of the 3σ uncertainty.

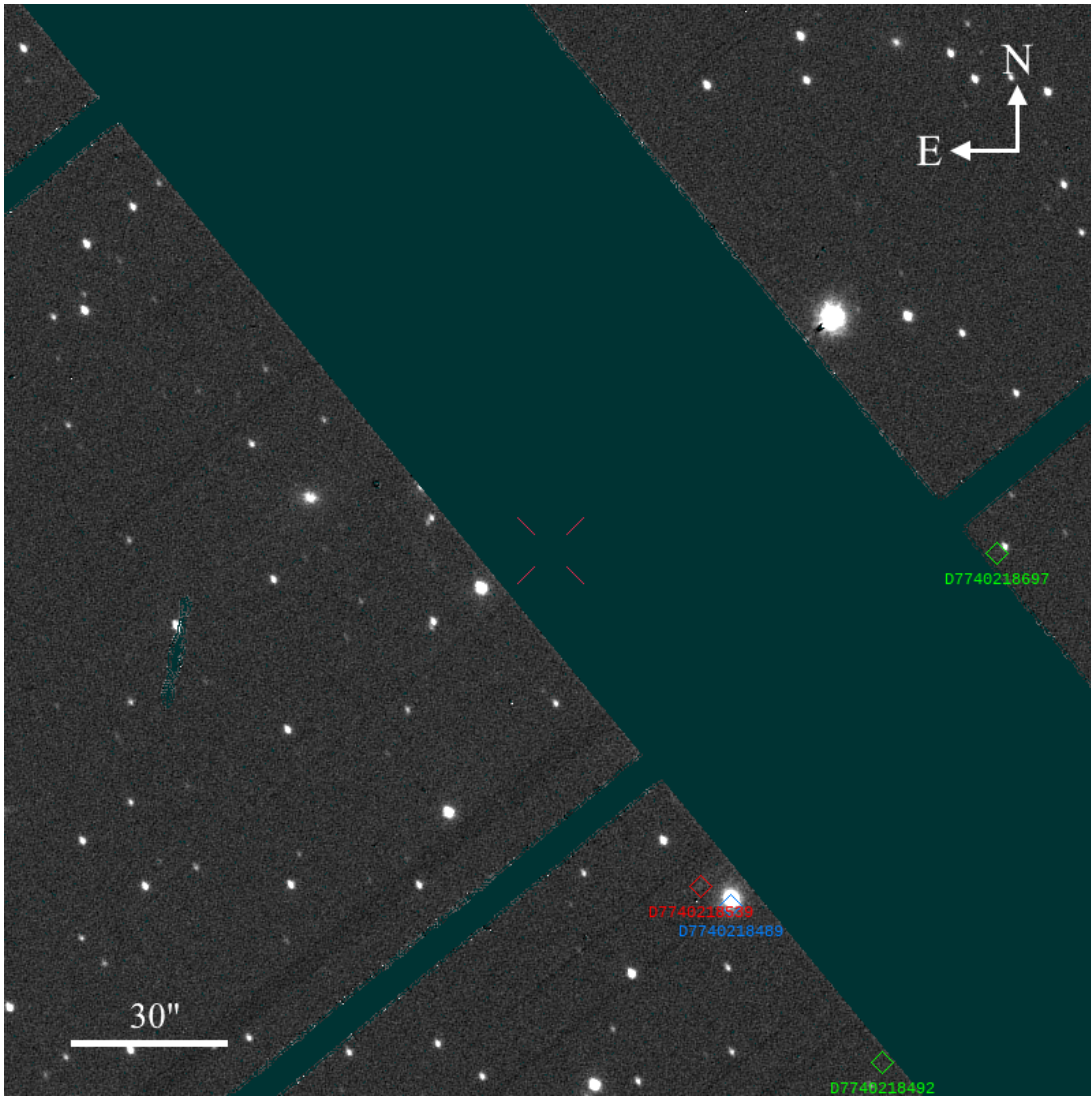


Figure 4. Preccovery image of 2I taken by PS1 on 2019 January 17. The comet’s nominal location, marked by a red crosshair, is in the chip gap.

the PS1 system on 2019 January 17 were identified, as summarized in Table 2. The normal processing for Pan-STARRS applies masking to remove areas not optimal for photometry because of non-uniform charge transfer efficiency, and for this study, the exposures were reprocessed without this mask. They were then visually inspected carefully over a large region centered at the expected ephemeris. The predicted ephemeris and uncertainty, however, place 2I firmly into a 70''-wide chip gap (Figure 4).

While no detections were found in the Pan-STARRS pre-discovery images, the fact that the expected location of 2I is contained within a chip gap favors the ZTF preccovery positions being correct, as even a weakly active comet should have been visible otherwise given the $G \sim 23$ limiting magnitude and near arcsecond seeing. The chip gap only occupies a small fraction ($\sim 10\%$ based on the astrometry up to 2019 October 1) of the uncertainty ellipse, therefore there was a much larger chance of being proven wrong.

However, we note that PS1 was not operational between 2018 August 23 and December 12 due to a dome shutter failure, and between 2019 February 10 and March 27 due to loss of power after a winter storm on Haleakala where the telescope is installed.

2.3. Catalina Sky Survey

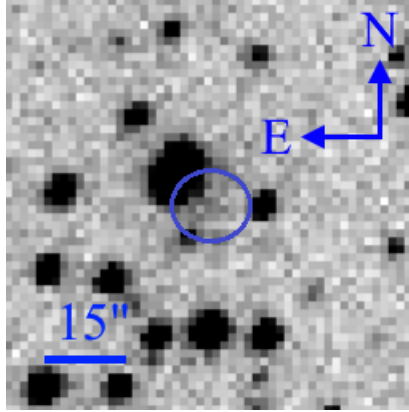


Figure 5. Preccovery image of 2I taken by the CSS 1.5 m telescope on 2019 March 1. The slight enhancement possibly corresponds to the comet is marked by a blue circle. The color is inverted.

The Catalina Sky Survey (CSS; e.g. Christensen et al. 2018) operates three telescopes dedicated to the discovery and follow-up of near-Earth objects: the 0.7 m Catalina Schmidt at Mt. Bigelow, a 1.0 m telescope and a 1.5 m telescope at Mt. Lemmon, Arizona.

Following a similar strategy of the Pan-STARRS data search, we searched the archival data of all three telescopes dating back to 2018 January 1. We identified various sets of images covering the predicted ephemeris of 2I: multiple sets of images taken by the 0.7 m Catalina Schmidt, but all dated no later than 2018 December 15, and a set of four images taken by the 1.5 m telescope on 2019 March 1.

The comet was too faint ($\gtrsim 1.5$ mag beyond the limit of the image) for the December 2018 and earlier images, while the March 2019 images reached a limiting magnitude that could be compatible with a faint detection of 2I. However, the position corresponding to the ZTF detections fell on a region heavily contaminated with background field sources. In three of the four frames, the object would have overlapped the PSF of a field star. The remaining frame was also marginally affected by an even brighter nearby star, but it might show a slight enhancement that is within 1.5–2 pixels from the predicted position of 2I (Figure 5). A deeper stack of historical images obtained by Catalina with the same telescope reveals no background source at that position, down to a limiting magnitude much fainter than the individual frame. Unfortunately, the enhancement was extremely faint, and might be compatible with a noise feature enhanced by the tails of the bright star’s point-source-function (PSF), making it difficult to draw a solid conclusion.

3. PHOTOMETRIC ANALYSIS

To measure the flux from 2I, we scale each frame with respect to a “reference” frame using the following formula and recombine the frames following the scheme in Table 2:

$$S = 10^{-0.4mag_{ZP,corr}} \left(\frac{\Delta}{\Delta_0} \right)^2 \left(\frac{r_H}{r_{H,0}} \right)^4 \quad (1)$$

where S is the scale coefficient; Δ and Δ_0 is the geocentric distance of the comet in the given frame and the reference frame, respectively; r_H and $r_{H,0}$ is the heliocentric distance of the comet in the given frame and the reference frame, respectively; and the corrected magnitude zero-point $mag_{ZP,corr}$ is defined by

$$mag_{ZP,corr} = mag_{ZP} + C_{img} \times C_{comet} \quad (2)$$

where mag_{ZP} is the magnitude zero-point and C_{img} is the color coefficient derived by the ZTF Science Data System and calibrated to the PS1 photometric system (Masci et al. 2019), and C_{comet} is the color of the comet. We use $C_{comet:g-r} = g_{PS1} - r_{PS1} = 0.54$ as measured by Guzik et al. (2019), with the colors converted using the relations derived in Tonry et al. (2012). The result is tabulated in Table 2.

We then fit the light-curve using the classic comet light-curve equation:

$$m_1 = M_1 + 5 \log \Delta + K_1 \log r_H + \Phi(\alpha) \quad (3)$$

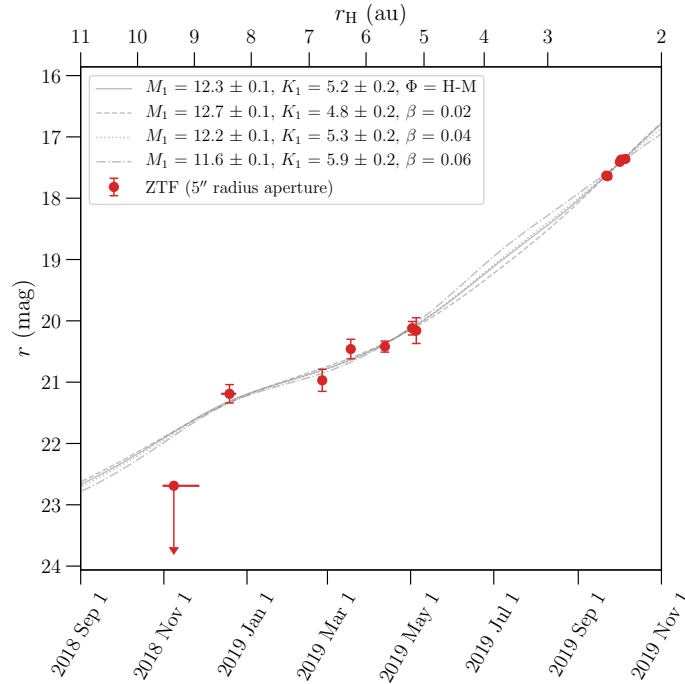


Figure 6. Best-fit light-curve of 2I using the pre-discovery photometry and recent ZTF photometry (MPEC 2019-V34). Horizontal bars indicate the time bin sizes. The light-curve functions being fitted are the Marcus model on Halley’s Comet (H-M), as well as linear phase functions assuming a phase coefficient of 0.02, 0.04 and 0.06 mag deg⁻¹. The bumps in December 2018 and July 2019 are caused by brightness enhancements at small phase angles during the opposition and conjunction of 2I.

where m_1 and M_1 are the apparent and absolute total magnitude of the comet, respectively, K_1 is the logarithmic heliocentric distance slope, and $\Phi(\alpha)$ is the phase function of the comet with respect to the phase angle α . We test four phase functions: the Marcus (2007) model on Halley’s Comet, as well as linear phase functions $\Phi(\alpha) = \alpha\beta$ where $\beta = 0.02, 0.04,$ and 0.06 mag deg⁻¹ is the phase coefficient of the comet (Lamy et al. 2004). All four models yield comparable results, with M_1 varies from 11.6 ± 0.1 to 12.7 ± 0.1 , and K_1 from 4.8 ± 0.2 to 5.8 ± 0.2 , as shown in Figure 6.

4. DISCUSSION

4.1. Driver of the Activity

The best-fit light-curve as shown in Figure 6 revealed a shallow slope, $K_1 = 5.3 \pm 0.2$, taking a linear phase coefficient $\beta = 0.04$ mag deg⁻¹. A shallow slope means that the activity stays largely constant as the comet approaches the Sun. Whipple (1978) shows that shallow brightening is common on the “dynamically new” solar system comets (with orbital periods $P \gg 10^4$ yr) which have $K_1 \in (5, 8)$), but uncommon on short-period comets and other long-period comets, which have $K_1 \gtrsim 10$, though his dataset is dominated by small heliocentric distances with $r_H < 5$ au. In this respect, 2I is analogous to dynamically new comets in the solar system.

The $K_1 = 5.3$ slope seemingly deviates from the data beyond ~ 8 au, preceded by what appears like a steep brightening phase, with $K_1 \approx 29$, though additional pre-discovery observations are needed to verify it. If such steep phase is real, it might indicate the onset of sublimation of cometary volatiles. The most compatible major volatile would be CO₂, which has an onset “knee” distance $r_H = 13$ au. Other cometary species, such as CH₃CN, HCN and CH₃OH, have similar turn-on distances (Meech & Svoren 2004), but they have low abundances in solar system comets (Cochran et al. 2015). CO, another cometary volatile commonly found on dynamically new comets in solar system that has an onset distance $r_H = 120$ au, is not as compatible. However, it has been suggested for the case of ‘Oumuamua that the volatiles may be buried beneath the surface and are only activated when the comet is much closer to the Sun, due to the time lag for the heat wave to penetrate to the depth of the ice (Fitzsimmons et al. 2018; Seligman & Laughlin 2018). Therefore, it is too early to exclude CO as the main driver of 2I’s activity.

To gain a deeper insight into the light-curve, we tested a sublimation model (Meech & Svoren 2004) that computes the amount of gas sublimating from an icy surface exposed to solar heating to explore the activity. The total brightness within a fixed aperture combines radiation scattered from both the nucleus and the dust dragged from the nucleus in the escaping gas flow, assuming a dust to gas mass ratio of 1. We used a nucleus radius of 0.5 km (Jewitt & Luu 2019), assumed an albedo of 0.04 for the nucleus and a linear phase function of 0.04 mag deg⁻¹ for the nucleus and 0.02 mag deg⁻¹ for the coma typical of other comets (Meech & Jewitt 1987; Krasnopolsky et al. 1987), a nucleus density of 400 kg m⁻³ similar to that seen for comets 9P/Tempel 1, 103P/Hartley 2 (Thomas 2009) and 67P/Churyumov-Gerasimenko (Pätzold et al. 2016), a grain density of 2000 kg m⁻³ (Rotundi et al. 2015), and large (10–100 μm) grains (Fitzsimmons et al. 2019). Unsurprisingly, our model confirmed that the activity of 2I must be driven by a species more volatile than water, since otherwise it would have been well below the detection limit of any of the surveys at ~ 5 au. We also found that the differences between the shape of the sublimation curves for CO and CO₂ near 8 au is minimal, so it is impossible to distinguish between these volatiles without further pre-discovery observations.

4.2. Size of the Nucleus

The non-detection in November 2018 data can be used to constrain the size of the nucleus. The effective cross-section area for scattering can be calculated using

$$C_e = \frac{\pi(1 \text{ au})^2}{p} 10^{-0.4(M_r - m_{\odot,r})} \quad (4)$$

where $p = 0.04$ is the assumed optical geometric albedo of the nucleus (Lamy et al. 2004), $m_{\odot,r} = -26.9$ is the apparent r -band magnitude of the Sun (Willmer 2018), and the absolute r -band magnitude (technically, the upper limit) M_r is defined as

$$M_r = m_r - 5 \log r_{\text{H}} \Delta - 2.5 \log \alpha \beta \quad (5)$$

with the variables following the same definitions for Equation 3. By inserting all the numbers, we have $C_e < 140 \text{ km}^2$ for the non-detection in November 2018, at 8.5 au. This upper bound indicates that the radius of the nucleus is no larger than ~ 7 km.

4.3. Active Area on the Nucleus

The size of the active area on the nucleus can be estimated with the knowledge of the mass loss rate of the comet and the mass flux of the activity-driving volatiles. The mass loss rate of 2I can be estimated using the cross-section area of the dust and the speed of the dust flow. By using Equation 4, we derive the cross-section area of coma to be ~ 280 to 360 km², from March to October 2019, in which r_{H} decreases from 6.4 to 2.6 au. The mass loss rate \dot{M} can be calculated by

$$\dot{M} = \frac{4\rho\bar{a}C_e}{3\tau} \quad (6)$$

where $\rho = 2000 \text{ kg m}^{-3}$ is the bulk density of the dust (Rotundi et al. 2015), which is admittedly not yet constrained for interstellar comets, but we do not have reason to believe it is much different from solar system comets, and therefore have assumed it to be analogous to the latter, $\bar{a} = 10^{-4} \text{ m}$, the characteristic size of the dust, is similarly assumed based on the observation of dynamically new solar system comets (e.g., Ye & Hui 2014; Jewitt et al. 2019), and τ is the timescale that a dust particle moves out of the aperture, which can be estimated by $\tau = l/v \approx 10^5 \text{ s}$, where l is the linear length of the aperture at the comet, and $v = 1 \text{ m s}^{-1}$ is the ejection speed of the dust. By inserting all the numbers, we obtain $\dot{M} \approx 10 \text{ kg s}^{-1}$, with the uncertainty around an order of magnitude mainly owing to the parameter \bar{a} (which can vary by an order of magnitude among solar system comets, cf. Fulle 2004).

We then solve the energy balance equation for CO and CO₂ ice, which are likely to be responsible for 2I's activity following the discussion in § 4.1, at the sub-solar point on the nucleus:

$$\frac{(1 - A_B)L_{\odot}}{4\pi r_{\text{H}}^2} = \epsilon\sigma T^4 + Z(T)L(T) \quad (7)$$

where $A_B = 0.01$ is the Bond albedo of the nucleus measured for 9P/Tempel 1 and 103P/Hartley 2 (Li et al. 2013b,a), L_{\odot} is the luminosity of the Sun, $\epsilon = 0.9$ is the infrared emissivity of the nucleus, σ is the Boltzmann constant, $L(T)$

is the latent heat of the sublimation of the ice, and $Z(T)$ is the mass flux. We solve $L(T)$ using the model by Cowan & A'Hearn (1979)³, and obtain $Z(T) \approx 3 \times 10^{-6} - 2 \times 10^{-5} \text{ kg m}^{-2} \text{ s}^{-1}$ from 6.4 au to 2.6 au for CO, and $1 \times 10^{-6} - 9 \times 10^{-6} \text{ kg m}^{-2} \text{ s}^{-1}$ for the same r_H span for CO₂. The active area required to support the mass loss rate would then be

$$A = \frac{\dot{M}}{(M_d/M_g)Z(T)} \quad (8)$$

where M_d/M_g is the dust-to-gas mass ratio, which is again unknown for interstellar comets. If we take $M_d/M_g = 1$ based on the measurement of long-period comet C/1995 O1 (Hale-Bopp) at similar heliocentric distance (Weiler et al. 2003), we have $A = 0.5 - 10 \text{ km}^2$ over the time span between December 2018 and September 2019, in line with the number derived by McKay et al. (2019) based on their observation in October 2019 (1.7 km²). Taking the upper limit of the size of the nucleus derived in § 4.2, the active fraction of 2I is $> 0.1\%$ of the nucleus. This is in line with the known solar system comets, which have fractional active area from a few 0.1% to $> 100\%$ (Tancredi et al. 2006), though we note that most of these measured comets are short-period comets with H₂O as the driving species. However, we caution that the uncertainty in A is about 1–2 orders of magnitude when we consider the uncertainties in \dot{M} and M_d/M_g , therefore the derived A and active fraction is highly uncertain.

4.4. Non-gravitational Accelerations and Implications

The inclusion of the precovery data in the orbit estimation process provides stringer constraints on the trajectory of 2I, but also introduces challenges to correctly model the dynamics. A gravity-only model of the orbit struggles to fit the data of March 2019 and earlier. In particular, the December 2018 position is rejected as an outlier (using the outlier rejection algorithm by Carpino et al. 2003). At this stage it is not entirely clear whether this behavior is caused by systematic errors in the bulk of the astrometric data, which were taken at low solar elongation and therefore at high airmass, or by non-gravitational accelerations. We note that non-gravitational accelerations were detected in the motion of ‘Oumuamua, despite the lack of visible outgassing (Micheli et al. 2018).

Table 1 reports JPL solution 20, which fits all the precovery observations and uses non-gravitational forces assuming CO as the primary driver (Yabushita 1996), more consistent than H₂O with the photometric data. The non-gravitational model for CO₂ is not available at this point; but since both CO and CO₂ are more volatile than water and that 2I was in the regime of both volatiles when it was observed, we believe that the two models should behave similarly over the fit span.

We also tested the rotation jet model (Chesley & Yeomans 2005), which computes the non-gravitational perturbations from a discrete number of jets, whose acceleration is averaged over a nucleus rotation. For the driver of the activity we again used CO. We considered two jets, a nearly polar one at 10° of colatitude and a mid-latitude one on the southern hemisphere at 135° of colatitude. Then, we scanned a raster for the spin pole’s Right Ascension (RA) and Declination (Dec), estimating the strengths of the two jets from the fit to the astrometry.

As shown in Fig. 7, we find two minima for the pole’s RA and Dec: (340°, 0°) and (185°, –25°). Because of the larger number of parameters, the jet model provides a better fit to the data than the Marsden et al. (1973) model. However, its reliability will need to be validated by the capability of making accurate predictions. Past experience has shown that the jet model can provide more accurate comet trajectory estimates (Farnocchia et al. 2016) and therefore the jet model solutions are worth consideration, especially as the observed arc extends into late 2019 and 2020.

5. CONCLUSIONS

The pre-discovery observations of newly-discovered interstellar comet 2I/Borisov revealed a comet that is observationally quite comparable to the long-period dynamically new comets in our own solar system. We found that 2I was active at 5–7 au, indicative of the presence of accessible ices more volatile than H₂O, such as CO and CO₂. A subsequent comprehensive follow-up campaign, presented by Bolin et al. (2019), reinforces this conclusion. We identified a possible steep brightening at 8–9 au might indicate an onset of activity at this distance, but more pre-discovery data, preferably from larger, multi-meter-sized telescopes, is needed to verify this behavior. We also found the nucleus to be no more than 7 km in radius, and that $\gtrsim 0.1\%$ of the surface is currently active, both are quite typical when compared to dynamically new solar system comets occasionally discovered and observed by surveys, though the derived size

³ <https://pdssbn.astro.umd.edu/SBNcgi/newiso.cgi>

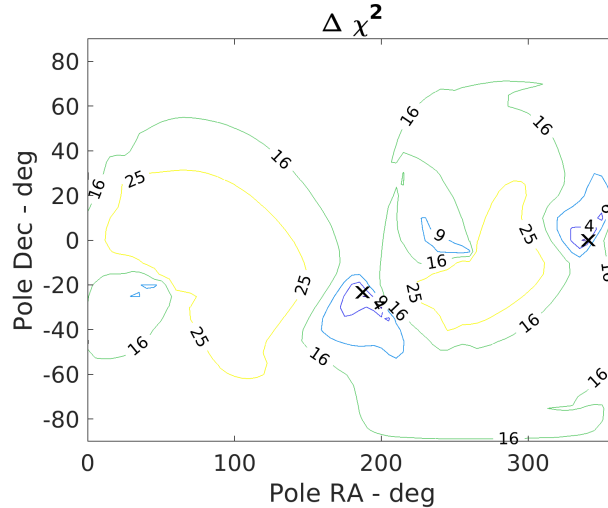


Figure 7. $\Delta\chi^2$ of the astrometric fit for the jet model as a function of the pole orientation. The two minima are marked with a black cross.

of active area is highly uncertain, mainly due to the uncertainties in nucleus size and dust size distribution. The pre-discovery observations also provides stringer constraints on the inbound trajectory and non-gravitational forces of 2I. We found that a CO model provides results that are more consistent with the observations compared to H_2O model.

It will be interesting to see if 2I continues to fit into the profile of dynamically new comets. For solar system comets, it is known that dynamically new comets are $10\times$ more likely to disintegrate than short-period comets, presumably due to their pristine state and weaker structural strength (Weissman et al. 2004). We note that independent analysis by Jewitt & Luu (2019) also suggested that 2I may be prone to disintegration based on its small nucleus size (sub-km-sized). Comets can disintegrate at large heliocentric distances, but most disintegrations seem to happen within ~ 2 au (Boehnhardt 2004), a distance that 2I will reach at its perihelion in December 2019. Survived dynamically new comets also tend to fade more rapidly after perihelion (Whipple 1978). Continued observations of 2I will enable further comparison to dynamically new comets in our solar system, and provide timely warning for any disintegration (or, as a less dramatic form, outburst) that may happen.

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Software: ZChecker (Kelley et al. 2019)

Facilities: PO:1.2m, PS1, SO:1.5m

REFERENCES

- Bellm, E. C., Kulkarni, S. R., Graham, M. J., et al. 2019, *PASP*, 131, 018002, doi: [10.1088/1538-3873/aaecbe](https://doi.org/10.1088/1538-3873/aaecbe)
- Boehnhardt, H. 2004, Split comets, ed. M. C. Festou, H. U. Keller, & H. A. Weaver, 301

- Bolin, B. T., Lisse, C. M., Kasliwal, M. M., et al. 2019, arXiv e-prints, arXiv:1910.14004. <https://arxiv.org/abs/1910.14004>
- Carpino, M., Milani, A., & Chesley, S. R. 2003, *Icarus*, 166, 248, doi: [10.1016/S0019-1035\(03\)00051-4](https://doi.org/10.1016/S0019-1035(03)00051-4)
- Chambers, K. C., Magnier, E. A., Metcalfe, N., et al. 2016, arXiv e-prints, arXiv:1612.05560. <https://arxiv.org/abs/1612.05560>
- Chesley, S. R., & Yeomans, D. K. 2005, in *IAU Colloq. 197: Dynamics of Populations of Planetary Systems*, ed. Z. Knežević & A. Milani, 289–302
- Christensen, E., Africano, B., Farneth, G., et al. 2018, in *AAS/Division for Planetary Sciences Meeting Abstracts*, 310.10
- Cochran, A. L., Lvasseur-Regourd, A.-C., Cordiner, M., et al. 2015, *SSRv*, 197, 9, doi: [10.1007/s11214-015-0183-6](https://doi.org/10.1007/s11214-015-0183-6)
- Cowan, J. J., & A’Hearn, M. F. 1979, *Moon and Planets*, 21, 155, doi: [10.1007/BF00897085](https://doi.org/10.1007/BF00897085)
- de León, J., Licandro, J., Serra-Ricart, M., et al. 2019, *Research Notes of the American Astronomical Society*, 3, 131, doi: [10.3847/2515-5172/ab449c](https://doi.org/10.3847/2515-5172/ab449c)
- Farnocchia, D., Chesley, S. R., Micheli, M., et al. 2016, *Icarus*, 266, 279, doi: [10.1016/j.icarus.2015.10.035](https://doi.org/10.1016/j.icarus.2015.10.035)
- Fitzsimmons, A., Snodgrass, C., Rozitis, B., et al. 2018, *Nature Astronomy*, 2, 133, doi: [10.1038/s41550-017-0361-4](https://doi.org/10.1038/s41550-017-0361-4)
- Fitzsimmons, A., Hainaut, O., Meech, K., et al. 2019, arXiv e-prints, arXiv:1909.12144. <https://arxiv.org/abs/1909.12144>
- Fulle, M. 2004, *Motion of cometary dust*, ed. M. C. Festou, H. U. Keller, & H. A. Weaver, 565
- Graham, M. J., Kulkarni, S. R., Bellm, E. C., et al. 2019, arXiv e-prints. <https://arxiv.org/abs/1902.01945>
- Guzik, P., Drahus, M., Rusek, K., et al. 2019, *Nature Astronomy*, 467, doi: [10.1038/s41550-019-0931-8](https://doi.org/10.1038/s41550-019-0931-8)
- Jewitt, D., Agarwal, J., Hui, M.-T., et al. 2019, *AJ*, 157, 65, doi: [10.3847/1538-3881/aaf38c](https://doi.org/10.3847/1538-3881/aaf38c)
- Jewitt, D., & Luu, J. 2019, arXiv e-prints, arXiv:1910.02547. <https://arxiv.org/abs/1910.02547>
- Kelley, M. S. P., Bodewits, D., Ye, Q., et al. 2019, in *ASP Conf. Ser.*, Vol. 471, *ADASS XXVIII*, ed. P. J. Teuben, M. W. Pound, B. A. Thomas, & E. M. Warner, 305
- Krasnopolsky, V. A., Moroz, V., Krysko, A., Tkachuk, A. Y., & Moreels, G. 1987, *A&A*, 187, 707
- Lamy, P. L., Toth, I., Fernandez, Y. R., & Weaver, H. A. 2004, *The sizes, shapes, albedos, and colors of cometary nuclei*, ed. M. C. Festou, H. U. Keller, & H. A. Weaver, 223
- Li, J.-Y., A’Hearn, M. F., Belton, M. J. S., et al. 2013a, *Icarus*, 222, 467, doi: [10.1016/j.icarus.2012.02.011](https://doi.org/10.1016/j.icarus.2012.02.011)
- Li, J.-Y., Besse, S., A’Hearn, M. F., et al. 2013b, *Icarus*, 222, 559, doi: [10.1016/j.icarus.2012.11.001](https://doi.org/10.1016/j.icarus.2012.11.001)
- Marcus, J. N. 2007, *International Comet Quarterly*, 29, 39
- Marsden, B. G., Sekanina, Z., & Yeomans, D. K. 1973, *AJ*, 78, 211, doi: [10.1086/111402](https://doi.org/10.1086/111402)
- Masci, F. J., Laher, R. R., Rusholme, B., et al. 2019, 131, 018003, doi: [10.1088/1538-3873/aae8ac](https://doi.org/10.1088/1538-3873/aae8ac)
- McKay, A. J., Cochran, A. L., Dello Russo, N., & DiSanti, M. 2019, arXiv e-prints, arXiv:1910.12785. <https://arxiv.org/abs/1910.12785>
- Meech, K. J., & Jewitt, D. C. 1987, *A&A*, 187, 585
- Meech, K. J., & Svoren, J. 2004, *Using cometary activity to trace the physical and chemical evolution of cometary nuclei*, ed. M. C. Festou, H. U. Keller, & H. A. Weaver, 317
- Meech, K. J., Weryk, R., Micheli, M., et al. 2017, *Nature*, 552, 378, doi: [10.1038/nature25020](https://doi.org/10.1038/nature25020)
- Micheli, M., Farnocchia, D., Meech, K. J., et al. 2018, *Nature*, 559, 223, doi: [10.1038/s41586-018-0254-4](https://doi.org/10.1038/s41586-018-0254-4)
- Opitom, C., Fitzsimmons, A., Jehin, E., et al. 2019, arXiv e-prints, arXiv:1910.09078. <https://arxiv.org/abs/1910.09078>
- ‘Oumuamua ISSI Team, Bannister, M. T., Bhandare, A., et al. 2019, *Nature Astronomy*, 3, 594, doi: [10.1038/s41550-019-0816-x](https://doi.org/10.1038/s41550-019-0816-x)
- Pätzold, M., Andert, T., Hahn, M., et al. 2016, *Nature*, 530, 63, doi: [10.1038/nature16535](https://doi.org/10.1038/nature16535)
- Rotundi, A., Sierks, H., Della Corte, V., et al. 2015, *Science*, 347, aaa3905, doi: [10.1126/science.aaa3905](https://doi.org/10.1126/science.aaa3905)
- Seligman, D., & Laughlin, G. 2018, *AJ*, 155, 217, doi: [10.3847/1538-3881/aabd37](https://doi.org/10.3847/1538-3881/aabd37)
- Tancredi, G., Fernández, J. A., Rickman, H., & Licandro, J. 2006, *Icarus*, 182, 527, doi: [10.1016/j.icarus.2006.01.007](https://doi.org/10.1016/j.icarus.2006.01.007)
- Thomas, N. 2009, *Planet. Space Sci.*, 57, 1106, doi: [10.1016/j.pss.2009.03.006](https://doi.org/10.1016/j.pss.2009.03.006)
- Tonry, J. L., Stubbs, C. W., Lykke, K. R., et al. 2012, *ApJ*, 750, 99, doi: [10.1088/0004-637X/750/2/99](https://doi.org/10.1088/0004-637X/750/2/99)
- Weiler, M., Rauer, H., Knollenberg, J., Jorda, L., & Helbert, J. 2003, *A&A*, 403, 313, doi: [10.1051/0004-6361:20030289](https://doi.org/10.1051/0004-6361:20030289)
- Weissman, P. R., Asphaug, E., & Lowry, S. C. 2004, *Structure and density of cometary nuclei*, ed. M. C. Festou, H. U. Keller, & H. A. Weaver, 337
- Whipple, F. L. 1978, *Moon and Planets*, 18, 343, doi: [10.1007/BF00896489](https://doi.org/10.1007/BF00896489)
- Willmer, C. N. A. 2018, *ApJS*, 236, 47, doi: [10.3847/1538-4365/aabdf](https://doi.org/10.3847/1538-4365/aabdf)
- Yabushita, S. 1996, *MNRAS*, 283, 347, doi: [10.1093/mnras/283.1.347](https://doi.org/10.1093/mnras/283.1.347)

Ye, Q.-Z., & Hui, M.-T. 2014, ApJ, 787, 115,

doi: [10.1088/0004-637X/787/2/115](https://doi.org/10.1088/0004-637X/787/2/115)

Ye, Q.-Z., Zhang, Q., Kelley, M. S. P., & Brown, P. G.

2017, ApJL, 851, L5, doi: [10.3847/2041-8213/aa9a34](https://doi.org/10.3847/2041-8213/aa9a34)

Yeomans, D., Chodas, P., Sitarski, G., Szutowicz, S., &

Królikowska, M. 2004, Comets II, 1, 137