Article

Early Observations of the Interstellar Comet 2I/Borisov

Chien-Hsiu Lee

NSF's National Optical-Infrared Astronomy Research Laboratory, Tucson, AZ 85719, USA; lee@noao.edu;
Tel.: +1-520-318-8368

check for
updates

Abstract: 2I/Borisov is the second ever interstellar object (ISO). It is very different from the first ISO 'Oumuamua by showing cometary activities, and hence provides a unique opportunity to study comets that are formed around other stars. Here we present early imaging and spectroscopic follow-ups to study its properties, which reveal an (up to) 5.9 km comet with an extended coma and a short tail. Our spectroscopic data do not reveal any emission lines between 4000–9000 Angstrom; nevertheless, we are able to put an upper limit on the flux of the C2 emission line, suggesting modest cometary activities at early epochs. These properties are similar to comets in the solar system, and suggest that 2I/Borisov—while from another star—is not too different from its solar siblings.

1. Introduction

2I/Borisov was first seen by Gennady Borisov on 30 August 2019. As more observations were conducted in the next few days, there was growing evidence that this might be an interstellar object (ISO), especially its large orbital eccentricity. However, the first astrometric measurements do not have enough timespan and are not of same quality, hence the high eccentricity is yet to be confirmed. This had all changed by 11 September; where more than 100 astrometric measurements over 12 days, Ref [1] pinned down the orbit elements of 2I/Borisov, with an eccentricity of 3.15 ± 0.13, hence confirming the interstellar nature. For comparison, the orbital elements of 2I/Borisov imply a hyperbolic excess speed of 30 km/s, comparable to and slightly larger than 'Oumuamua [2], whose excess speed was 26 km/s. More interestingly (and unlike 'Oumuamua), 2I/Borisov showed an extended coma and a broad, short tail ($\sim 15''$) in short g'- and r'-band exposures taken on 10 September 2019 [1]. Thus, it is clear that this second-known interstellar interloper is a comet.

It is known that comets in our solar system can serve as a reservoir of the primordial materials of the proto-planetary disk when the planets were formed and as the disk cooled down. Hence, the interstellar comet 2I/Borisov provides a unique opportunity to probe chemical compositions of other exo-planetary systems. We note that unlike 'Oumuamua, 2I/Borisov was spotted very early on. It was at a distance of ~ 3 a.u. on 30 August, and the existence of a short tail indicates that its cometary activities just started, and we can still probe the pristine material on its surface. We expect, as this interstellar comet is on its way in (perihelion at ~ 2 a.u.), that the tail will develop further. Here we present early observations, at the epoch of 17 September 2019 UT.

2. Observation

From JPL/HORIZONS, it was predicted that 2I/Borisov could brighten to V = 18.5 mag around September 2019. We were not only aiming at the comet nucleus, but also the cometary tail as well, which can be much fainter than the nucleus. Hence, we conducted imaging observations with a total of 600-second integrations in the V-band with the Alhambra Faint Object Spectrograph and Camera (ALFOSC) mounted on the 2.5 m Nordic Optical Telescope. In 600-second integration time, ALFOSC

can reach to V = 22 mag with a signal-to-noise ratio (S/N) ∼20. The field of view (FoV) of ALFOSC is 6.4 × 6.4 squared arcminutes, sampled by 2048 × 2048 pixels in the imaging mode, translating into 0.2138 arcsec/pixel. To better remove CCD artifacts and cosmic rays, we divided the total 600-second integration into 3 × 200-second single exposures, each of them reaching to S/N ∼ 10 at V = 22 mag. Even in the single exposure, 2I/Borisov was bright enough to allow us to align and stack individual exposures into a deeper stack.

In addition to imaging, we also performed spectroscopic observations to search for emission lines that can be indicative of outgassing molecules of 2I/Borisov. We employed the g4 grism of ALFOSC, to cover the C2 emission lines (4700 Ang. $< \lambda <$ 6000 Ang.) and potential absorption features from hydrated silicates at 7000 Ang. With 10-minute integration time using a 2.5-arcsecond slit under a median sky condition (1.5-arcsecond seeing condition under 1.5 airmass during grey nights), we expect to reach a S/N ∼20 of the continuum. This sufficiently allows us to detect the above-mentioned features in the spectra. The slit was aligned to a fixed position angle (90 degrees, east of north) with atmospheric dispersion corrector to correct for atmospheric differential refraction. To enable the removal of cosmic rays and CCD artifacts, we thus divided the 600 s integration into 3 × 200-second single exposures.

The above-mentioned observations, both photometrically and spectroscopically, were conducted on 17 September 2019 UT, between 5 and 6 a.m. Data reduction and analysis were performed in a standard fashion, making use of the Image Reduction and Analysis Facility (IRAF). The photometric observations were de-trended with bias subtraction and flat fielding. After de-trending, we further aligned the three individual images and median combined them into a deeper image. The spectra were also reduced with corresponding bias subtraction, flat fielding, and wavelength-calibration against ThAr lamp. To remove cosmic ray and CCD artifacts, the three individual spectra were median combined into a single, deeper spectrum.

3. Result and Discussion

Our deep imaging (Figure 1) clearly detects 2I/Borisov, with an extended coma (compared to field stars, see Figure 1) and a short tail, spanning ∼15 arcsec in anti-solar direction (with a position angle of ∼300 degrees). To extract the photometry from the imaging, we used SExtractor [3]. Adopting a circular aperture with a radius of 20 arcseconds and calibrated using field stars against the APASS survey, we estimated the comet to be V = 18.93 ± 0.03 mag. Given the brightness, we can estimate the size of the comet as follows. We computed the absolute magnitudes H_V using

$$H_V = m_V - 5log_{10}(r_H \Delta) - \Phi(\alpha), \tag{1}$$

where r_H and Δ are the helio- and geo-centric distances (in a.u.) respectively. $\Phi(\alpha)$ is the phase function given a phase angle α. We assume $\Phi(\alpha) = \beta\alpha$ and β = 0.04 mag/degree. With the absolute magnitude in hand, we can further calculate the effective scattering cross-section C_e by

$$C_e = \frac{1.5 \times 10^6}{p_V} \times 10^{-0.4H_V}, \tag{2}$$

where p_V corresponds to the V-band geometric albedo. As the albedo of 2I/Borisov is yet to be determined, here we assume p_V = 0.05 [4] for the comet nuclei, which is similar to the albedo distribution of primitive class asteroids. Using the above-mentioned equations, the mean magnitude corresponds to C_e = 108 km^2. This translates into an equal-area circle of radius $\sqrt{\frac{C_e}{\pi}}$ = 5.9 km; assuming a nominal density ρ = 0.5 × 10^3 kg/m^3 from the Rosetta observations of comet Churyumov–Gerasimenko [5], we estimate the mass of 2I/Borisov to be 2 × 10^{14} kg. We should note that the photometry is affected by the extended coma, and hence the estimates (both size and mass) should be treated as an upper limit. Nevertheless, even with this upper limit, the size and the

mass of 2I/Borisov are in similar ranges of the comets in the solar system [4,6]. We note that our independent observations lead to the results similar to [1,7–9].
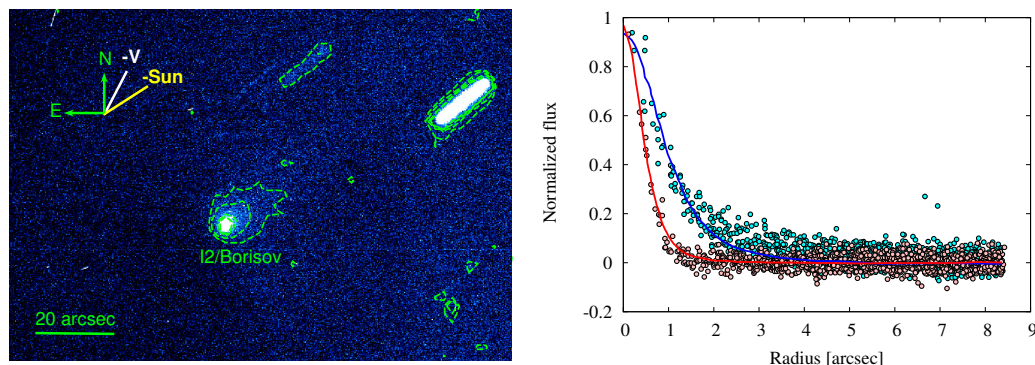

Figure 1. Left: V-band imaging of 2I/Borisov. The direction of the velocity and the Sun, and the North (to the up) and East (to the left) are marked accordingly. The contours indicate the appearance of an extend coma. **Right**: brightness profile of 2I/Borisov (cyan filled circles) and a field star taken under sidereal tracking (pink filled circles). The blue and red lines indicate the best-fit point-spread-function. The brightness profile of 2I/Borisov significantly different from a point-source (field star), suggesting the existence of an extend coma.

It has been reported that the reflectance spectrum of 2I/Borisov is similar to that of comets and D-type asteroids seen in the solar system [10]. However, in our spectrum there is no sign of emission lines, especially C2 (4700 Ang. $< \lambda <$ 6000 Ang.), which are prominent features seen in the comets in the solar system. We employ a procedure similar to that of [11] to obtain an upper limit from the non-detection of the C2 lines. We first calibrate the spectral continuum using the broad-band photometry. As we only have V-band (λ_c = 5500 Ang.) in hand, we thus focus on the C2 emission lines. On 17 September 2019, we measured V = 18.93 magnitude for 2I/Borisov. Since a V= 0 (Vega) star has a flux density $f_\lambda = 3.75 \times 10^{-9}$ erg/cm^2/s/Ang. [12], we can infer the mean V-band continuum flux density of 2I/Borisov to be $f_V = 1.0 \times 10^{-16}$ erg/cm^2/s/Ang. The strong C2ΔV = 0 band is confined in the wavelength range of 5050–5220 Ang. [13], yet there is no detection in our spectrum of 2I/Borisov. To quantify the level of non-detection, we made use of the continuum adjacent to the C2ΔV = 0 band with equal width, both blueward and redward at the corresponding wavelength ranges of B_C at 4880 Ang. $< \lambda <$ 5049 Ang. and R_C at 5221 Ang. $< \lambda <$ 5390 Ang., respectively (as marked in Figure 2). We estimated uncertainties statically (expressed in terms of fractions of the continuum) of B_C, C2, and R_C as 0.17, 0.19, and 0.18, respectively. We used the largest uncertainty among the three, i.e., 1σ = 0.19, as the fractional uncertainty in the continuum in the C2ΔV-band. This provided an empirical upper limit of the gas flux density $f_{C2} = 0.57 \times f_V = 5.7 \times 10^{-17}$ erg/cm^2/s/Ang. at 3 σ-level. By summing up the flux in the $\Delta\lambda$ = 170 Ang. of the C2ΔV-band, we further estimated an upper limit of the flux $F = f_{C2} \times \Delta\lambda < 9.7 \times 10^{-15}$ erg/cm^2/s at 3 σ-level. We note the non-detection of C2 lines could be due to our shallow spectrum, or because the comet is at lower activity at this epoch; the surface activity could increase significantly as it approaches perihelion. We note that our independent spectroscopic observations lead to the results similar to [7,14,15].
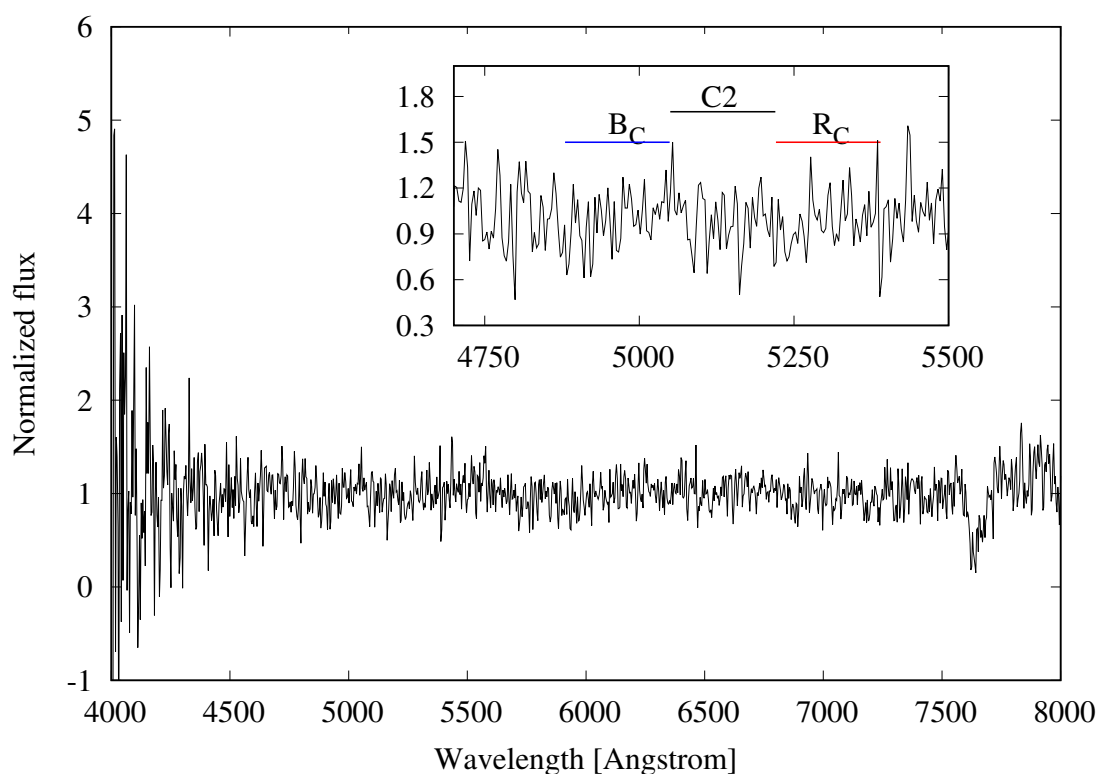
Figure 2. Normalized optical spectrum of 2I/Borisov. There are no traces of strong emission lines. Inset: Normalized spectrum of 2I/Borisov at the wavelength of C2ΔV = 0 emission (5050 Ang. $< \lambda <$ 5220 Ang.). The horizontal lines mark the wavelengths of the C2 band and the blue and red continua (B_C and R_C) used to estimate the noise.

To summarize, both imaging and spectroscopy show that 2I/Borisov shares similar properties with comets in the solar system, hence it is unremarkable except for it being ejected from another star. However, we should note that comet ejection is not uncommon, and can happen in the solar system due to the migration of giant planets, as predicted by the Nice model [16–18]. Current astrometric data indicate that 2I/Borisov came from and will return to a radiant close to the direction of open star cluster Stock 2 [10]. However, we should note that given its speed (∼30 km/s), Stock 2 would not be at its current location and could not have been the origin of 2I/Borisov after it travelled ∼33,000 years. We will be able to better determine the trajectory of 2I/Borisov after it passes perihelion; combining with the exquisite astrometry of nearby stars with Gaia, we will be able to pin down its home star. Furthermore, with LSST on the horizon, we will be able to identify incoming interstellar objects early on; this will enable fly-by or sample-return missions, e.g., comet interceptors, to provide in situ investigations of interstellar objects. Another possibility is that some of the interstellar objects (comets and asteroids) can become trapped in the solar system by three-body gravitational interactions involving Jupiter and the Sun (Lingam & Loeb 2018). Hence, it would be possible to carry out in situ explorations in more detail.

References

1. Guzik, P.; Drahus, M.; Rusek, K.; Waniak, W.; Cannizzaro, G.; Pastor-Marazuela, I. Initial characterization of interstellar comet 2I/Borisov. *arXiv* **2019**, arXiv:1909.05851.
2. Meech, K.J.; Weryk, R.; Micheli, M.; Kleyna, J.T.; Hainaut, O.R.; Jedicke, R.; Wainscoat, R.J.; Chambers, K.C.; Keane, J.V.; Petric, A.; et al. A brief visit from a red and extremely elongated interstellar asteroid. *Nature* **2017**, *552*, 378. [CrossRef] [PubMed]
3. Bertin, E.; Arnouts, S. SExtractor: Software for source extraction. *Astron. Astrophys. Suppl. Ser.* **1996**, *117*, 393. [CrossRef]
4. Fernández, Y.R.; Kelley, M.S.; Lamy, P.L.; Toth, I.; Groussin, O.; Lisse, C.M.; A'Hearn, M.F.; Bauer, J.M.; Campins, H.; Fitzsimmons, A.; et al. Thermal properties, sizes, and size distribution of Jupiter-family cometary nuclei. *Icarus* **2013**, *226*, 1138. [CrossRef]
5. Jorda, L.; Gaskell, R.; Capanna, C.; Hviid, S.; Lamy, P.; Ďurech, J.; Faury, G.; Groussin, O.; Gutiérrez, P.; Jackman, C.; et al. The global shape, density and rotation of Comet 67P/Churyumov-Gerasimenko from preperihelion Rosetta/OSIRIS observations. *Icarus* **2016**, *277*, 257. [CrossRef]
6. Britt, D.T.; Consolmagno, G.J.; Merline, W.J. Small body density and porosity: New data, new insights. In Proceedings of the 37th Annual Lunar and Planetary Science Conference, The Woodlands, TX, USA, 21–25 March 2016.
7. Fitzsimmons, A.; Hainaut, O.; Meech, K.J.; Jehin, E.; Moulane, Y.; Opitom, C.; Yang, B.; Keane, J.V.; Kleyna, J.T.; Micheli, M.; et al. Detection of CN gas in Interstellar Object 2I/Borisov. *Astrophys. J. Lett.* **2019**, *885*, L9. [CrossRef]
8. Jewitt, D.; Luu, J. Initial Characterization of Interstellar Comet 2I/2019 Q4 (Borisov). *arXiv* **2019**, arXiv:1910.02547.
9. Bolin, B.T.; Lisse, C.M.; Kasliwal, M.M.; Quimby, R.; Tan, H.; Ye, Q.; Copperwheat, C.; Fernandez, Y.R.; Lin, Z.Y.; Morbidelli, A.; et al. haracterization of the Nucleus, Morphology and Activity of Interstellar comet 2I/Borisov by Optical and Near-Infrared GROWTH, Apache Point, IRTF, ZTF, Keck and HST Observations. *arXiv* **2019**, arXiv:1910.14004.
10. De León, J.; Licandro, J.; Serra-Ricart, M.; Cabrera-Lavers, A.; Font Serra, J.; Scarpa, R.; de la Fuente Marcos, C.; de la Fuente Marcos, R. Interstellar Visitors: A Physical Characterization of Comet C/2019 Q4 (Borisov) with OSIRIS at the 10.4 m GTC. *Res. Notes Am. Astrono. Soc.* **2019**, *3*, 131. [CrossRef]
11. Jewitt, D.; Kim, Y.; Luu, J.; Rajagopal, J.; Kotulla, R.; Ridgway, S.; Liu, W. Episodically Active Asteroid 6478 Gault. *Astrophys. J. Lett.* **2019**, *876*, L19. [CrossRef]
12. Drilling, J.S.; Landolt, A.U. *Allen's Astrophysical Quantities*; Springer: Berlin, Germany, 2000; Volume 381.
13. Farnham, T.L.; Schleicher, D.G.; A'Hearn, M.F. The HB narrowband comet filters: Standard stars and calibrations. *Icarus* **2000**, *147*, 180. [CrossRef]
14. Kareta, T.; Andrews, J.; Noonan, J.W.; Harris, W.M.; Smith, N.; O'Brien, P.; Sharkey, B.N.; Reddy, V.; Springmann, A.; Lejoly, C.; et al. Carbon Chain Depletion of 2I/Borisov. *arXiv* **2019**, arXiv:1910.03222.
15. Opitom, C.; Fitzsimmons, A.; Jehin, E.; Moulane, Y.; Hainaut, O.; Meech, K.J.; Yang, B.; Snodgrass, C.; Micheli, M.; Keane, J.V.; et al. 2I/Borisov: A C2-depleted interstellar comet. *Astron. Astrophys.* **2019**, *631*, L8. [CrossRef]
16. Tsiganis, K.; Gomes, R.; Morbidelli, A.; Levison, H.F. Origin of the orbital architecture of the giant planets of the Solar System. *Nature* **2005**, *435*, 459. [CrossRef] [PubMed]
17. Morbidelli, A.; Levison, H.F.; Tsiganis, K.; Gomes, R. Chaotic capture of Jupiter's Trojan asteroids in the early Solar System. *Nature* **2005**, *435*, 462. [CrossRef] [PubMed]
18. Gomes, R.; Levison, H.F.; Tsiganis, K.; Morbidelli, A. Origin of the cataclysmic Late Heavy Bombardment period of the terrestrial planets. *Nature* **2005**, *435*, 466. [CrossRef] [PubMed]