Interstellar comet 2I/Borisov

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Interstellar comets penetrating through the Solar System were anticipated for decades[1,2]. The discovery of non-cometary 1I/‘Oumuamua by Pan-STARRS was therefore a huge surprise and puzzle. Furthermore, its physical properties turned out to be impossible to reconcile with Solar System objects[3-5], which radically changed our view on interstellar minor bodies. Here, we report the identification of a new interstellar object which has an evidently cometary appearance. The body was identified by our data mining code in publicly available astrometric data. The data clearly show significant systematic deviation from what is expected for a parabolic orbit and are consistent with an enormous orbital eccentricity of 3.14 ± 0.14. Images taken by the William Herschel Telescope and Gemini North telescope show an extended coma and a faint, broad tail – the canonical signatures of cometary activity. The observed g’ and r’ magnitudes are equal to 19.32 ± 0.02 and 18.69 ± 0.02, respectively, implying g’-r’ color index of 0.63 ± 0.03, essentially the same as measured for the native Solar System comets. The discovery of this object indicates that interstellar comets might be common and creates a tremendous opportunity to study the first such object in detail.

On 8 September 2019 at 04:15 UT, we were alerted by our software "Interstellar Crusher" (see Methods) of a new hyperbolic object. The body was discovered by Gennady Borisov on 30 August 2019 at 01:03 UT and received a provisional label gb00234. Its permanent designation will likely be 2I/Borisov. On 11 September 2019, publicly available astrometric data allowed us to confirm the hyperbolic orbit of this object at 15-σ significance. Using 127 positions obtained over a 12.42-day interval we obtained an osculating hyperbolic solution that is presented in Table 1. The enormous eccentricity of 3.14 ± 0.14, together with the perihelion distance of 1.96 ± 0.04 au, imply a hyperbolic excess speed of ~ 30 km s^{-1}. The body entered the Solar System from the direction ~ 70° off the Solar apex with the asymptotic radiant at RA = 02^h 08^m and Dec = 59.7° in the constellation of Cassiopeia. In Figure 1 we present astrometric residuals of 2I/Borisov calculated for hyperbolic (left panel) and parabolic (right panel) orbital solutions. While a systematic trend is clearly visible for the parabolic solution, the residuals are much smaller and evenly distributed in the hyperbolic case. Residual analysis together with the large hyperbolic excess velocity assure that 2I/Borisov is of extrasolar origin. Since the body arrives from the direction off the ecliptic plane, the hyperbolic orbit cannot be explained by planetary perturbations inside the Solar System, and the observed residuals are few orders of magnitude too large to be accounted to non-gravitational forces observed in Solar System comets.

We observed this object on 10 September 2019 UT using the 4.2 m William Herschel Telescope (WHT) on La Palma and the 8.2 m Gemini North telescope at Maunakea. WHT data were obtained with the Auxiliary-port CAMera (ACAM) at 05:38 UT (mid-point) and comprise ten sidereal-tracked 60-sec exposures, of which five were obtained in g' and five in r' bands[6]. Gemini data were collected with the Gemini Multi-Object Spectrograph (GMOS-

N) at 14:57 UT with non-sidereal tracking and comprise four g'-band and four r'-band exposures taken with 60-sec integration time. Both data sets were obtained at low elevation (22° to 27°) in morning twilight. At the time of the observations, the helio- and geocentric distances of 2I/Borisov were equal to 2.76 and 3.42 au, respectively, and the phase angle was 14°. The images were corrected for overscan, bias and flatfield in the standard fashion, and then combined separately in the two bands. They reveal an extended coma and a broad, short tail emanating in roughly antisolar direction (Figure 2). We see no clear difference in morphology in the two bands. The brightness measured in a 2.0-arcsec radius photometric aperture is equal to 19.32 ± 0.02 mag in g' and 18.69 ± 0.02 mag in r', implying the g'-r' color index of 0.63 ± 0.03 mag.

Both orbital and morphological properties of this body show that this is the first certain case of an interstellar comet, and the second-known interstellar minor body identified in the Solar System. The extended coma and broad tail displayed by the object stand in stark contrast with the purely asteroidal appearance of 'Oumuamua. The measured color is slightly redder than the solar g'-r' = 0.45 ± 0.02 mag[7], which is perfectly consistent with the colors of the Solar System's long period comets[8]. The body was discovered on its way to perihelion (9 December 2019 at 1.96 au) and before the closest approach to Earth (28 December 2019 at 1.89 au), thus the overall visibility will be gradually improving. 2I/Borisov is destined for an unprecedented observing campaign lasting many months (Figure 3) that will allow us to gain sensational insights into the physical properties of interstellar comets and exosolar planetary systems in general. The discovery of an interstellar comet shows that such bodies might be common and thus the former expectations[1,2] were probably valid. More discoveries are expected in near future thanks to LSST.

Methods

Interstellar Crusher

“Interstellar Crusher” is a custom Python3 code working on Widows Subsystem for Linux (WSL). It operates on Bill Gray’s Find_Orb. While continuously monitoring astrometric positions reported on the Possible Comet Confirmation Page, it is performing a real-time search for hyperbolic orbits among newly discovered minor bodies. The detection of a possible interstellar object raises an alarm that is sent via an e-mail.

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Competing Financial Interests

The authors declare that they have no competing financial interests.

Figure Legends

Figure 1 | Astrometric residuals of 2I/Borisov calculated for parabolic and unrestricted (hyperbolic) solutions. Top and bottom left panels show the residuals of astrometric data compared to best parabolic fit in Right Ascension and Declination respectively. Right panels show the residuals of astrometric data compared to best hyperbolic fit in Right Ascension and Declination accordingly. Mean residuals are 0.59 arcsec and 1.30 arcsec for hyperbolic and parabolic solution respectively.

Figure 2 | Median-stacked images of 2I/Borisov from Gemini North. Left panel shows the image in the g' band and right panel shows the image in r' band.

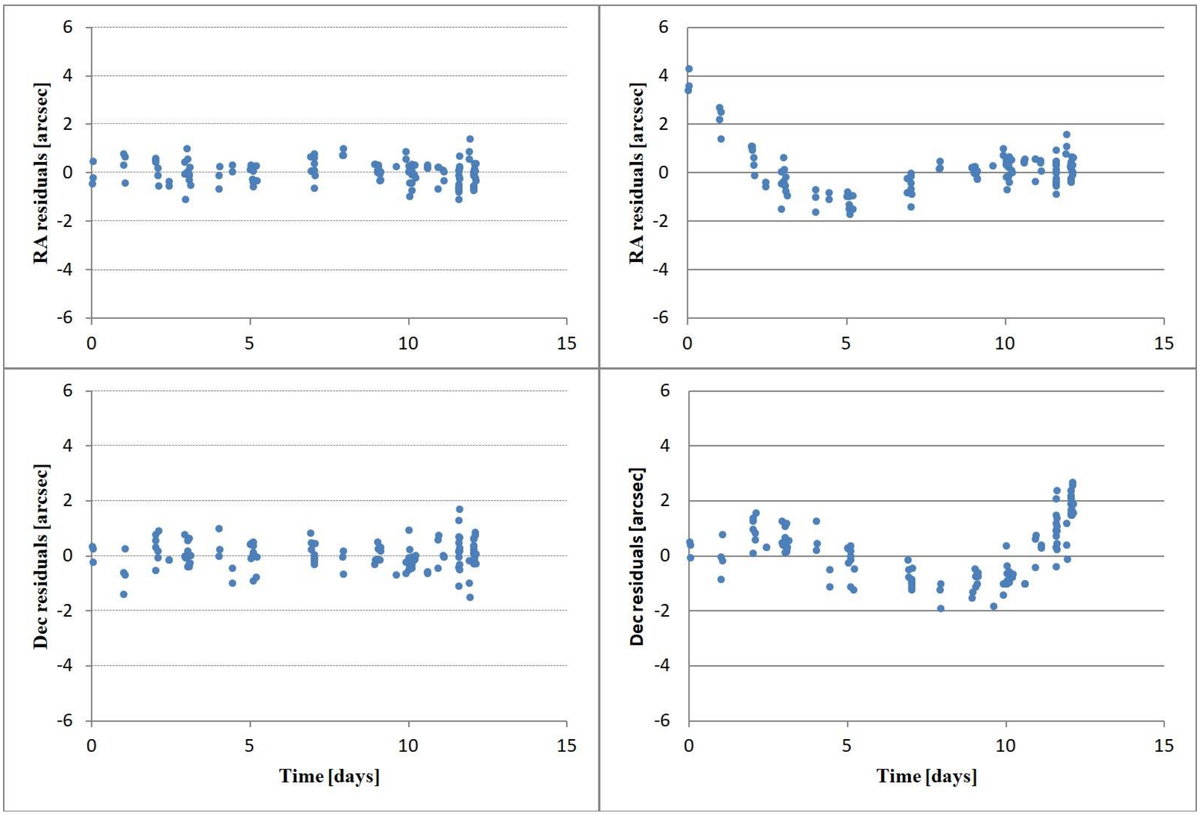
Figure 3 | Visibility prospects of 2I/Borisov in the upcoming months. Top panel illustrates basic geometric circumstances and bottom panel shows r'-band magnitude extrapolated from our measurement for different photometric models. We adopted the canonical form of photometric models for active comets $m = H + 5.0 \log(\Delta) + 2.5\, n \log(r)$, where m is the observed magnitude, H is the absolute magnitude (at 1 au from Earth and Sun), n is a free parameter (typically $n \sim 4$), Δ (au) is the geocentric, distance and r (au) is the heliocentric distance.

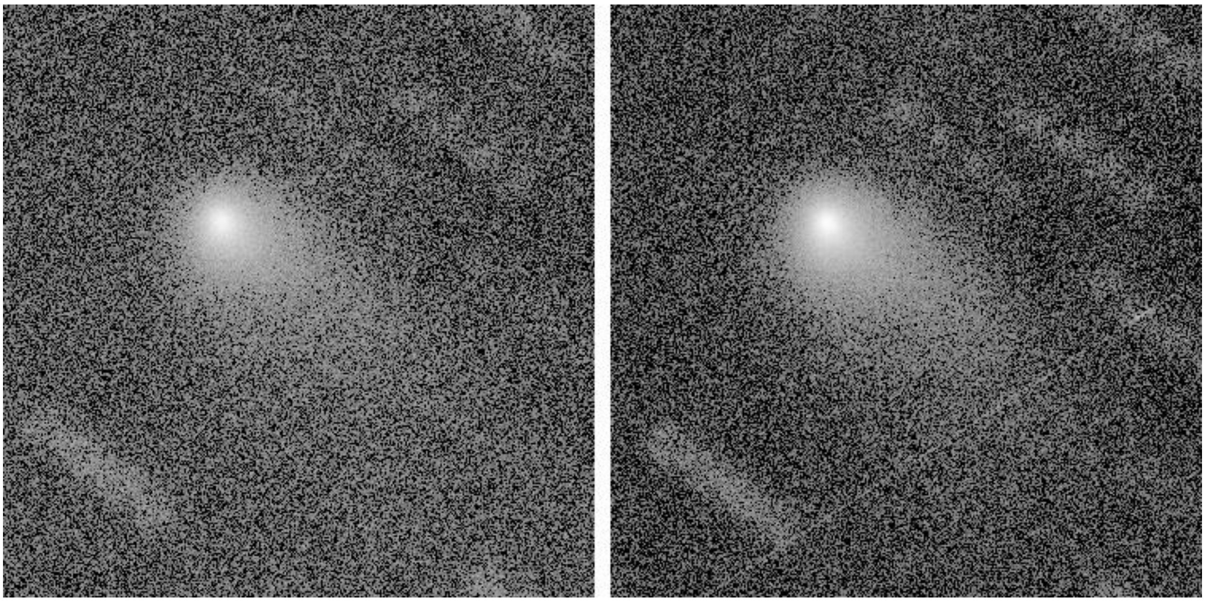
Tables

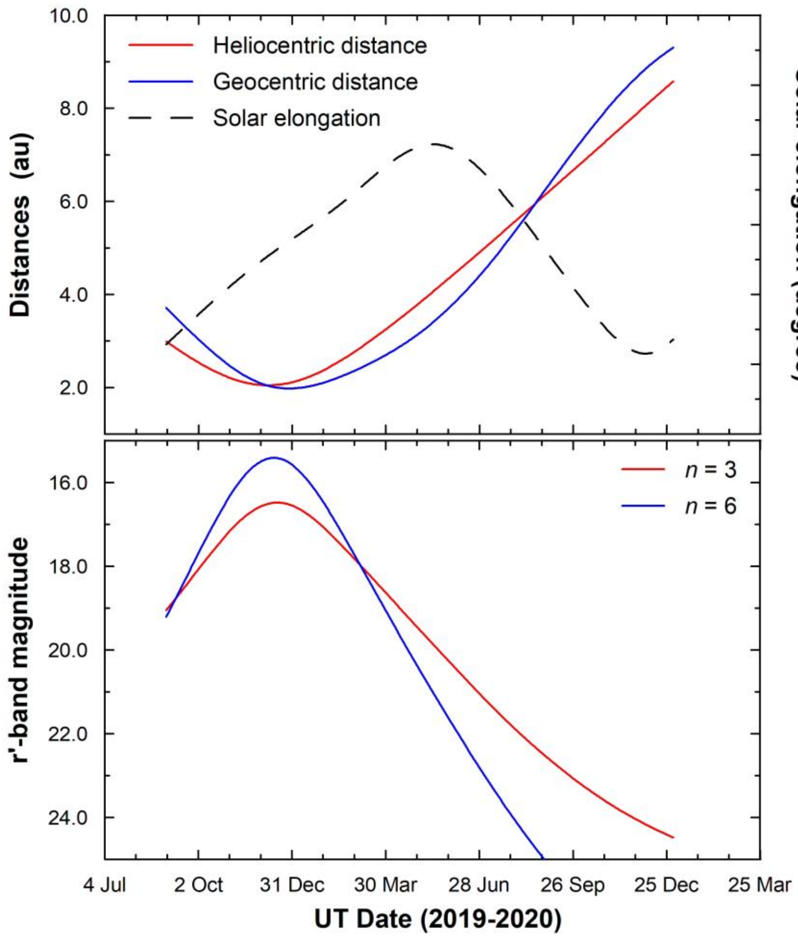
Table 1 | Hyperbolic orbital elements of 2I/Borisov calculated for the osculation epoch 2019 Sep. 11.0 TT.

T	2019 Dec. 9.745968 ± 0.94 TT
e	3.1551235 ± 0.13
q	1.95954186 ± 0.035 au
$\boldsymbol{\omega}$	210.22059 ± 0.90 deg (2000.0)
$\boldsymbol{\Omega}$	307.71365 ± 0.33 deg (2000.0)
i	44.49503 ± 0.34 deg (2000.0)

Figures


RA residuals [arcsec]
Dec residuals [arcsec]
Time [days]
6
4
2
0
-2
-4
-6
0
5
10
15





10.0
8.0
6.0
4.0
2.0
Distances (au)
Solar elongation (degree)
Heliocentric distance
Geocentric distance
Solar elongation
16.0
18.0
20.0
22.0
24.0
r'-band magnitude
n = 3
n = 6
4 Jul
2 Oct
31 Dec
30 Mar
28 Jun
26 Sep
25 Dec
25 Mar
UT Date (2019-2020)