Spectrophotometric characterization of Interstellar Comet 2I/Borisov before perihelion passage

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Interstellar Comet 2I/Borisov

Motivation

- Is the exchange of materials between two different planetary systems possible?
- How does this interstellar comet behave in the vicinity of the Sun?
- Are the interstellar objects comparable to the ones from our solar system?

Related work

- According to several studies, 2I is very similar to the Solar System comets
- High resolution imaging: r_n = 0.2 - 0.5 km [Jewitt et al., 2019]
- Dust production rate estimations:
  - 30 kg/s (Sep) - Fitzsimmons et al. 2019
  - 35 kg/s (Nov) - Cremonese et al. 2020
  - 52 kg/s (late Sep) – León et al., 2019
  - 200 kg/s (early Dec) - Yang et al. 2021

Our contribution

- Simultaneously photometry in four bands (g,r,i,z_s)
- Monitored the color indices and scattering cross-section during an interval of 2 months
- Applied a dust production model for our data

Comet trajectory

Figure 1: The comet location on its hyperbolic trajectory in the first night (3rd Oct. 2019) and the last night (13th Dec. 2019) of observations. The images were created using NASA JPL Small-Body Database Browser.

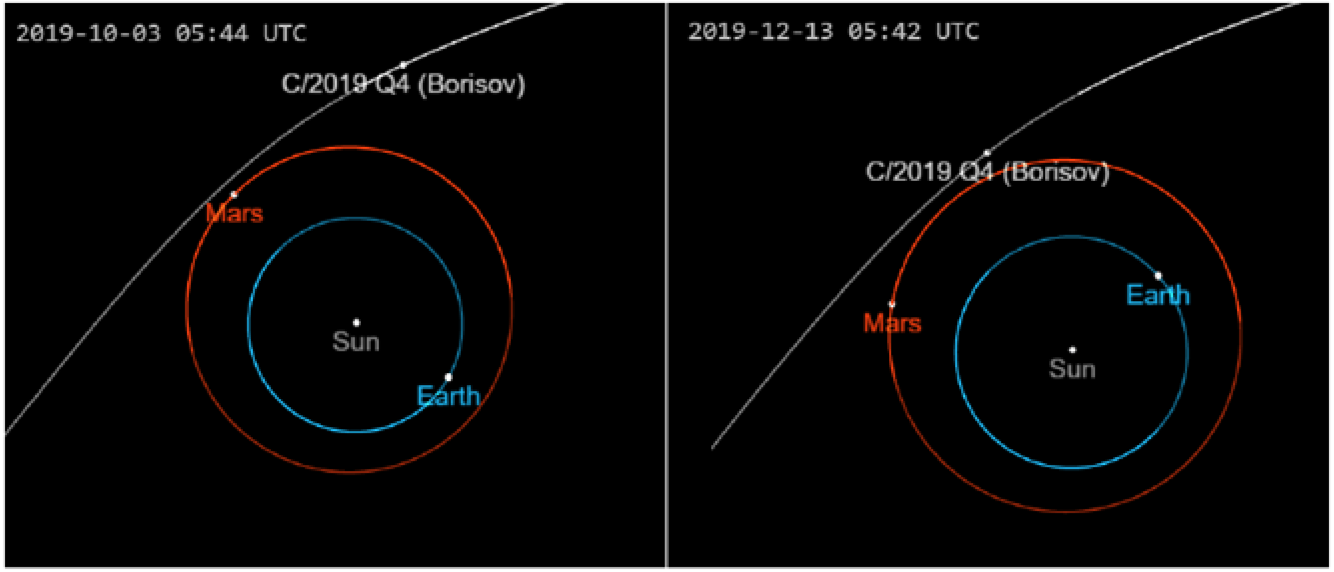


Figure 2: Composed Image of 2I/Borisov obtained using TCS in g, r, i bands (2- Nov. 2019)

perihelion distance q (AU)	eccentricity e	perihelion time t_p	inclination i (deg)	excess velocity v_∞ (km/s)
2.006581	3.35621	2019-Dec-08.5450	44.052570	32.2822

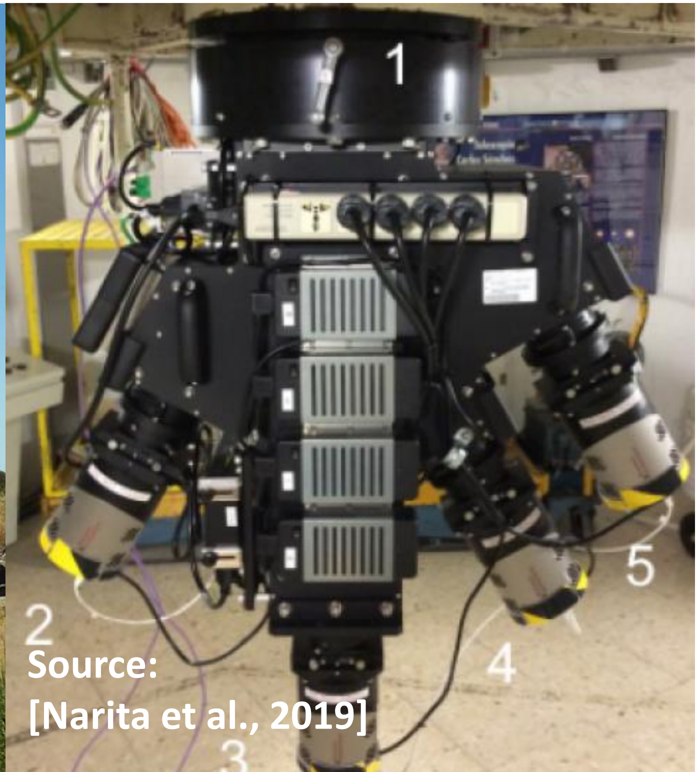
Table 1: Orbital parameters of 2I/Borisov retrieved from JPL Small-Body Database Browser and velocity excess from [J. De León et al. 2019]

Instrumentation

2I/Borisov Observations
Sep - Dec 2019

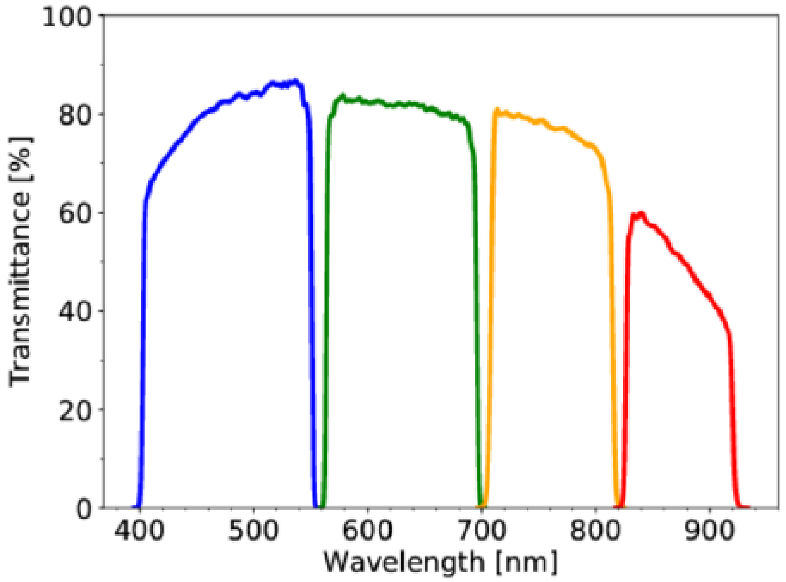
Teide Observatory
Canary Islands

1.52 m Cassegrain
auto-guiding system, remote



Source:
[Narita et al., 2019]

Figure 3: Transmittance as a function of wavelength for MuSCAT2 filters. Source: [Narita et al., 2019].



- Cassegrain focus (1)
- CCD cameras
  g, r, i, z_s(2-5)

Data reduction

Table 2: Observations log

Obs Night	Frames	r (AU)	Δ (AU)
2019-10-03	91	2.485	2.974
2019-10-04	55	2.472	2.953
2019-10-05	104	2.460	2.932
2019-10-07	83	2.435	2.891
2019-10-12	109	2.374	2.790
2019-10-13	100	2.362	2.770
2019-10-14	89	2.351	2.751
2019-10-15	62	2.339	2.731
2019-11-01	84	2.171	2.424
2019-11-02	137	2.162	2.408
2019-11-07	83	2.123	2.330
2019-11-10	63	2.102	2.286
2019-11-22	31	2.039	2.133
2019-12-10	29	2.006	1.984
2019-12-13	25	2.009	1.969

2.2 - 1.5 air masses

Calibration steps

1. astrometric calibration *Gaia Data Release 2*
2. photometric calibration *Pan-STARRS catalogues*
3. finding the zeropoint

Processed data: 15 nights
Need post-processing: 9 nights
Software: Photometry Pipeline – PP [Mommert, M. 2017]

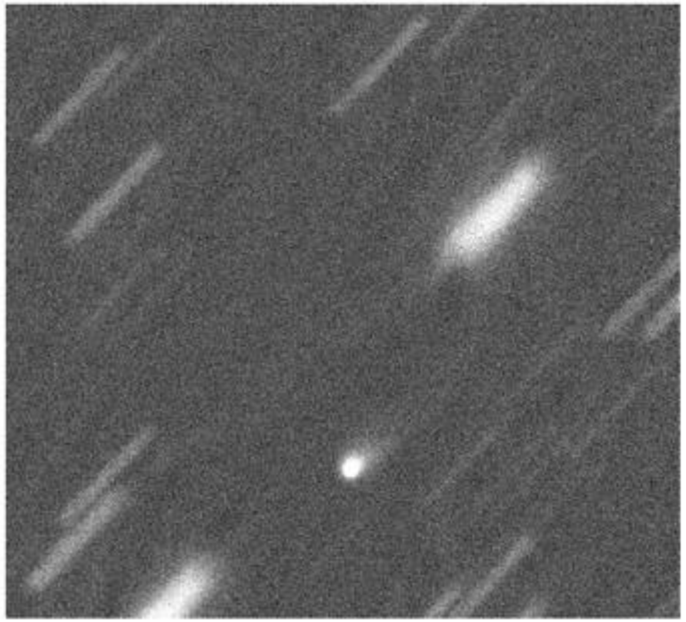
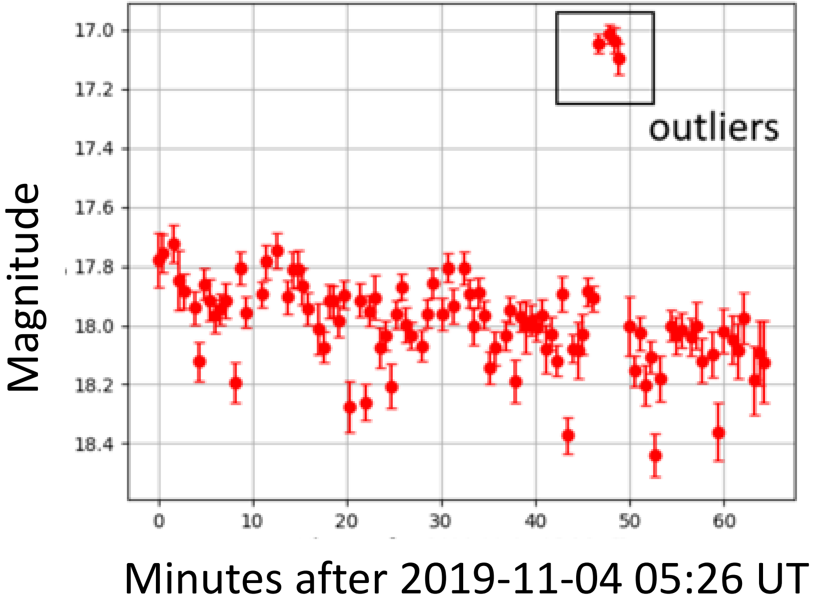


Figure 4: Composite r-band image (83 frames, 7 Oct) created with PP

Figure 5: Light-curve outliers due to background sources



Dust production model

$$f(a) = g_0 e^{-\frac{a_0}{a}} \left(\frac{a_0}{a}\right)^{\alpha}$$ [U. Fink, M. Rubin 2012]

g_0 = normalisation constant
α = free parameter, usually around 4
a_p = most probable particle size

$$C_e = \int_{a_{min}}^{a_{max}} q_s(a,\lambda)\pi a^2 f(a) da$$

$a_0 = \alpha \cdot a_p$

α = 4
a_p = 1 mm
ρ = 2650 kg/m^3 [Yang et al., 2021]
n = 1.80 + 0,075j (Mg-Fe sillicates – 620 nm) [Busarev et al., 2021]

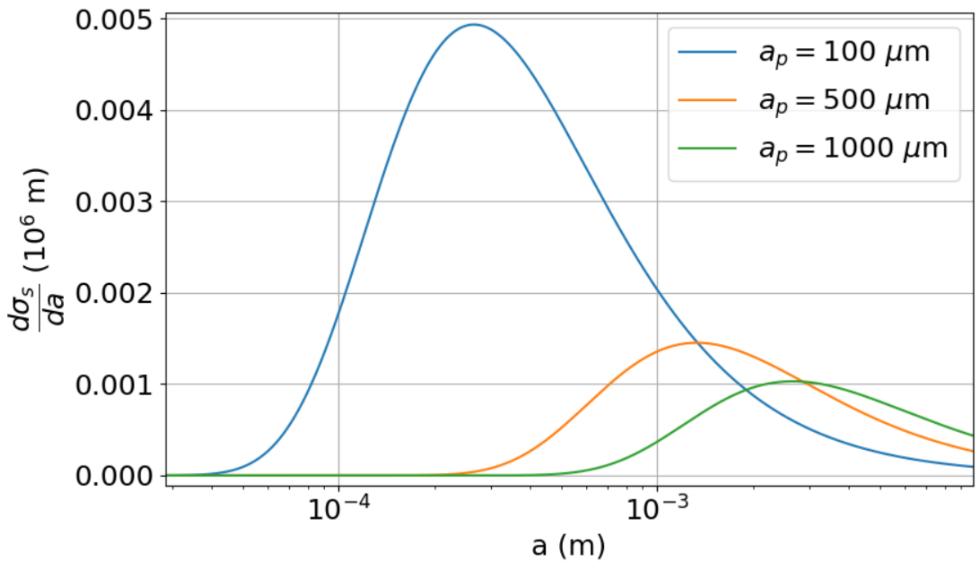


Figure 6: Particles size distribution

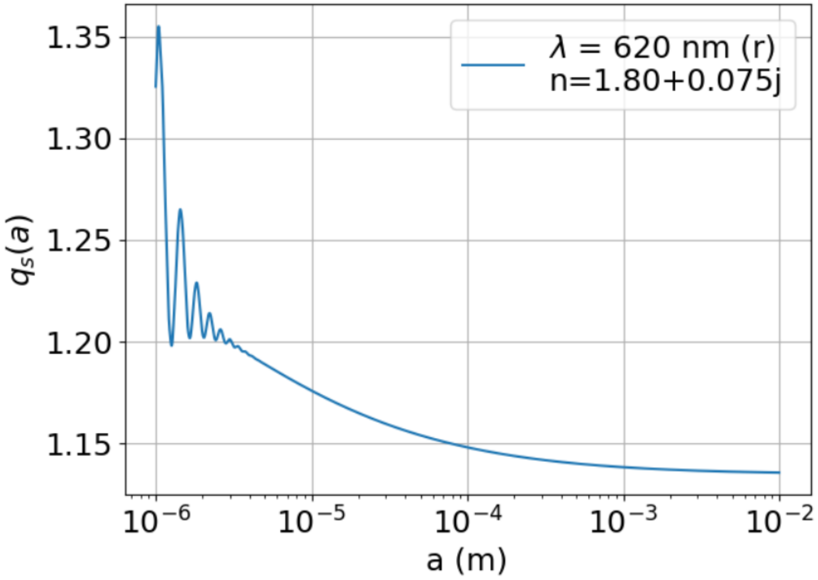


Figure 7: Scattering efficiency as a function of particle size according to Mie theory

Morphology

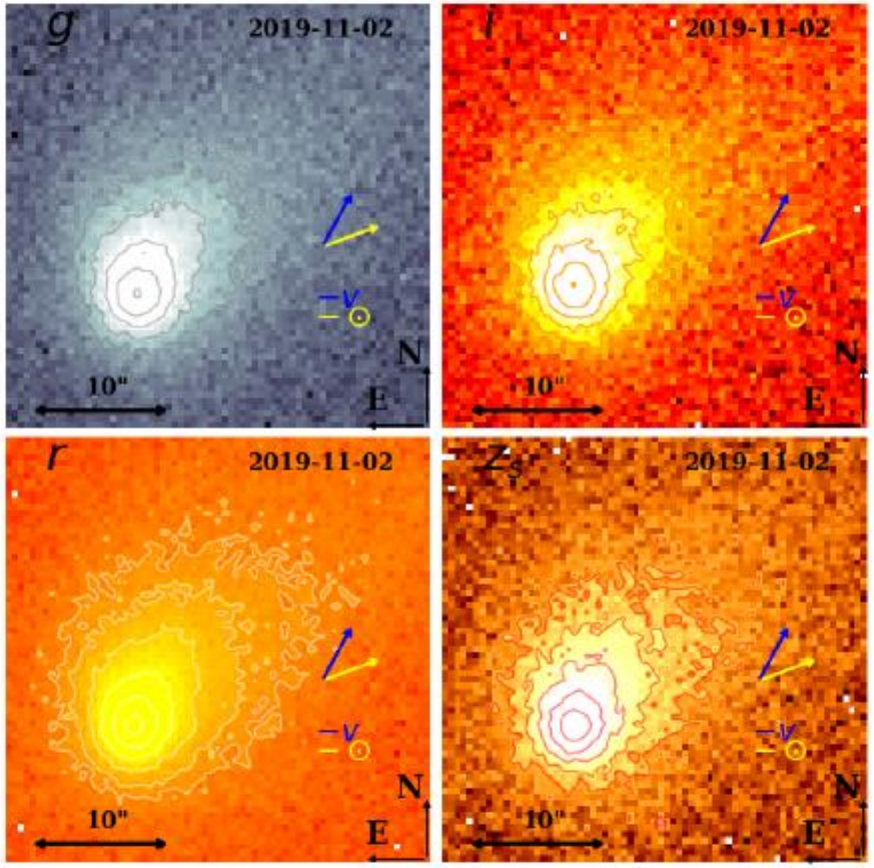
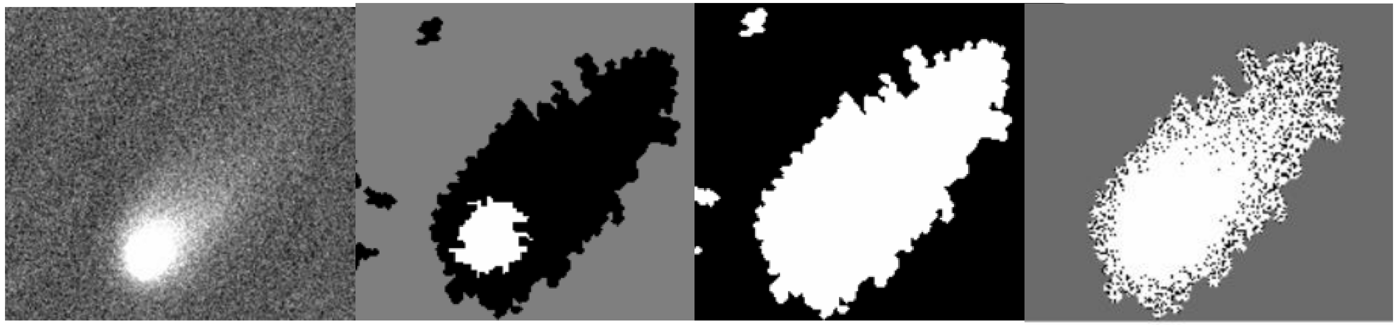


Figure 8: Multi-band photometry images

Figure 10: Comet profile extracted by NoiseChisel tool of GnuAstro library [M. Akhlaghi and T. Ichikawa, 2015] on 2 Novemver



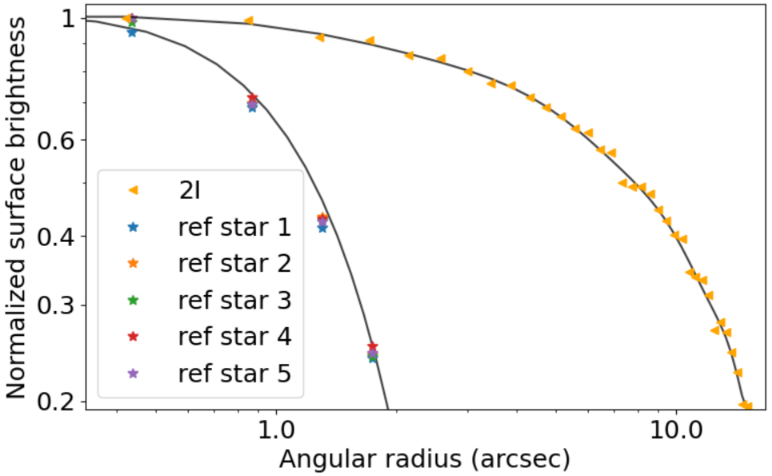


Figure 9: Normalized surface brightness of the comet and reference star

At 2^{nd} November 2019:

$\theta_{tail} = 65''$

$\Rightarrow L = \frac{\theta\Delta}{\sin\alpha} = 2.8 \times 10^{8}$ m

Color indices

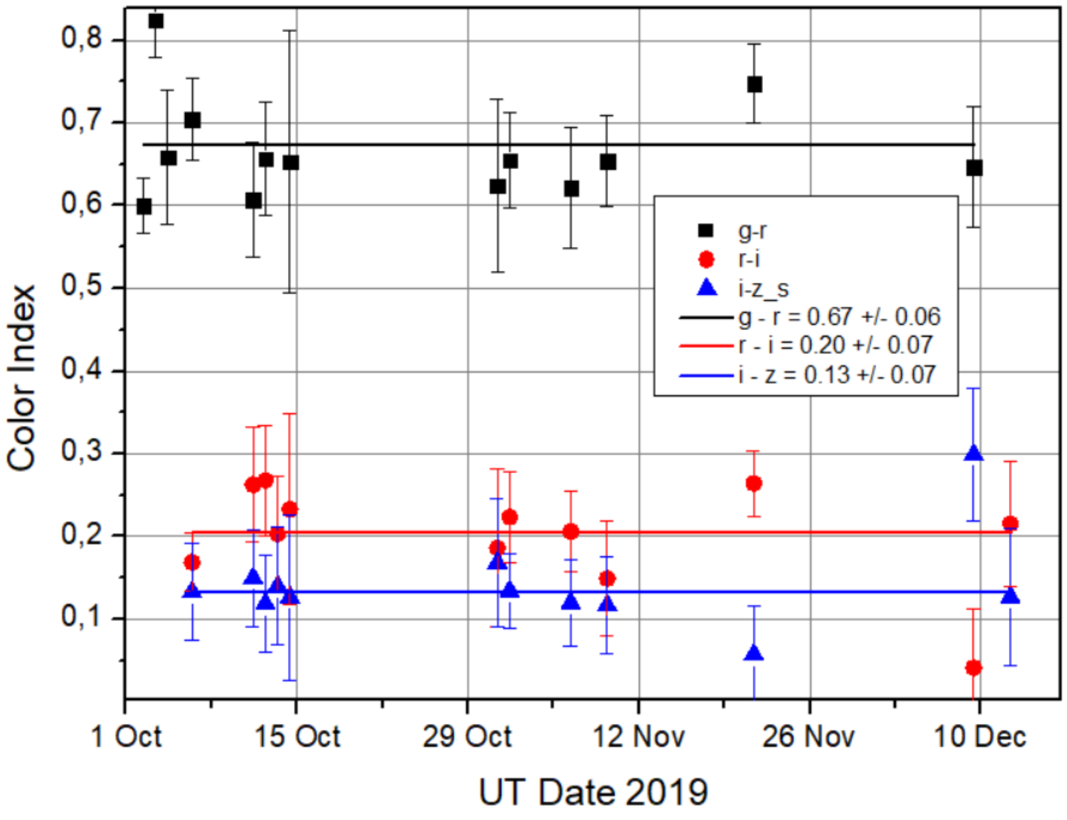
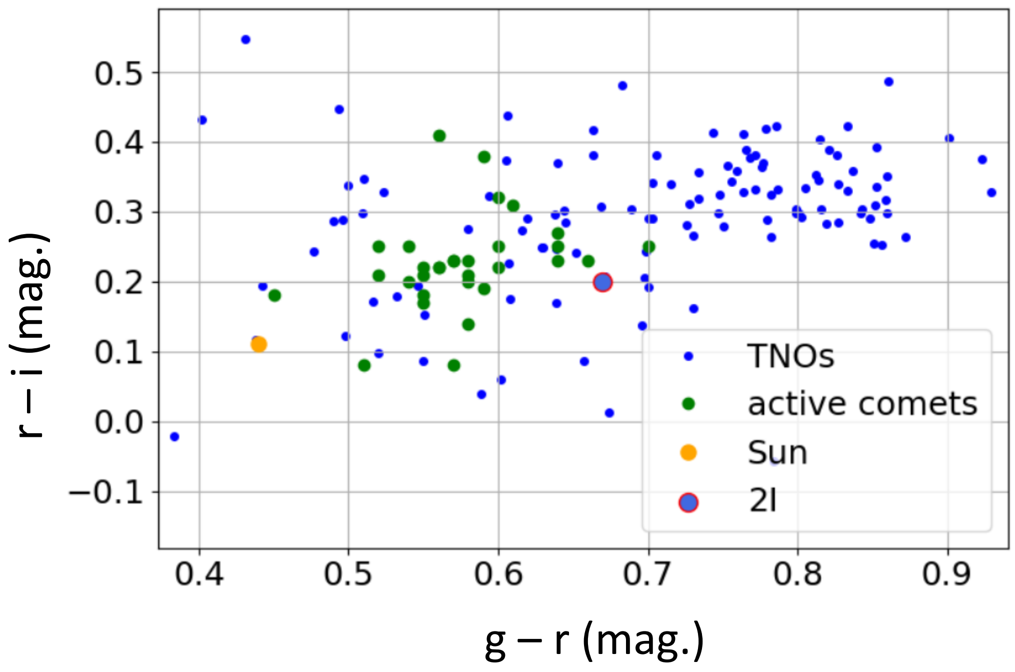


Figure 11: 2I/Borisov color indices as a function of time.

Figure 12: The color diagram r – i vs g – r of 2I, active comets [M. Solontoi et al., 2012] and Trans-Neptunian objects of the Solar System [Eran O. Ofek, 2012]



Outburst

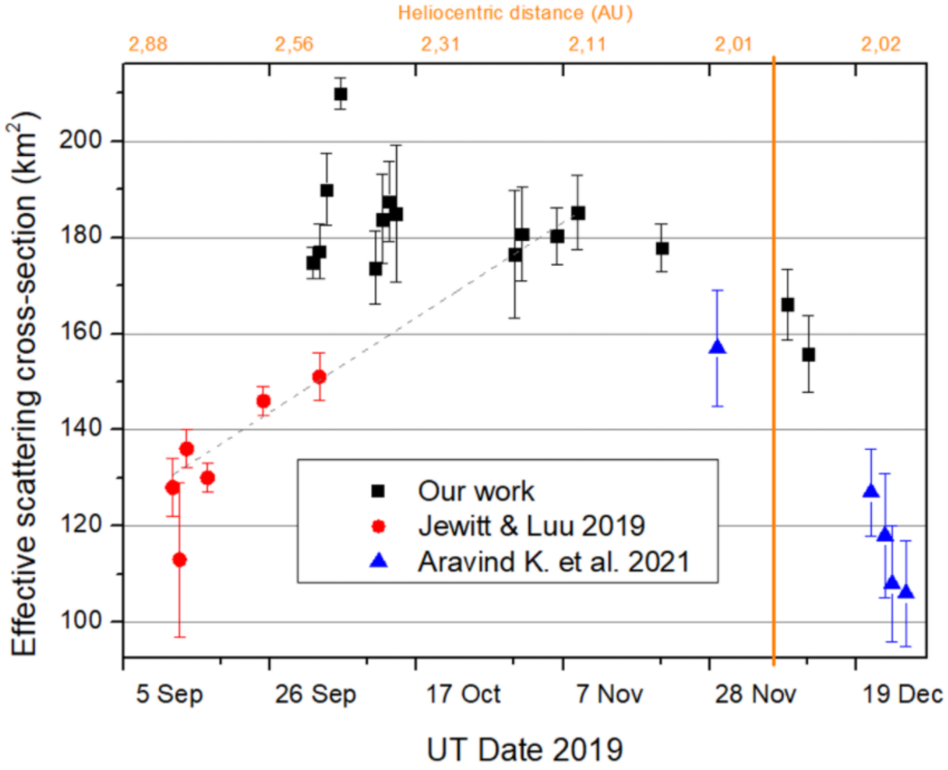


Figure 13: The effective scattering cross-section as a function of time. A comparison to Jewitt and Luu 2019 and Aravind K. et al 2021

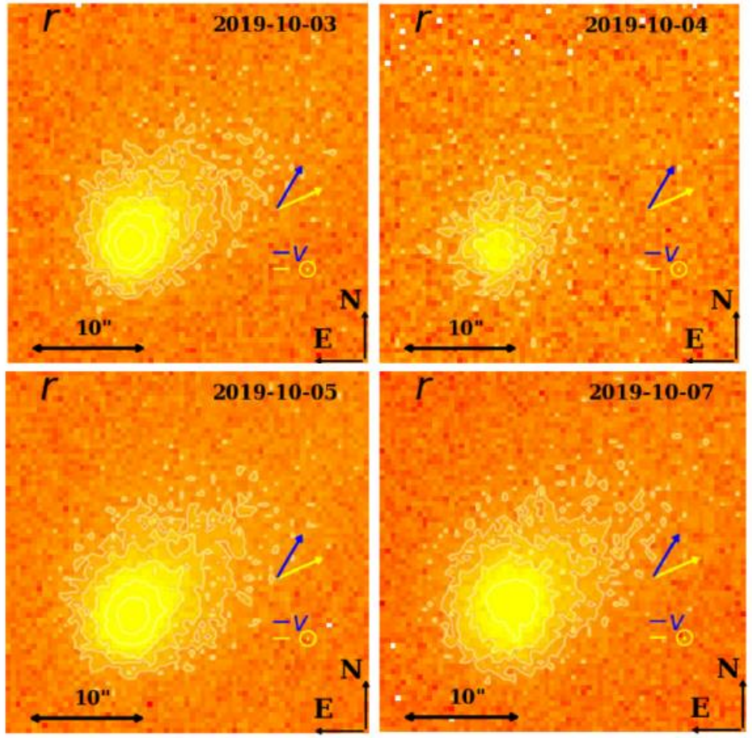


Figure 14: The comet images in r-band during the mini-outburst after overcoming the water-ice line at 2.5 AU

When computing the total effective scattering cross-section:
p_V = 0.1 (geometric albedo)
15,000 km aperture

Dust production rate

Figure 15: The mass of dust in coma as a function of time

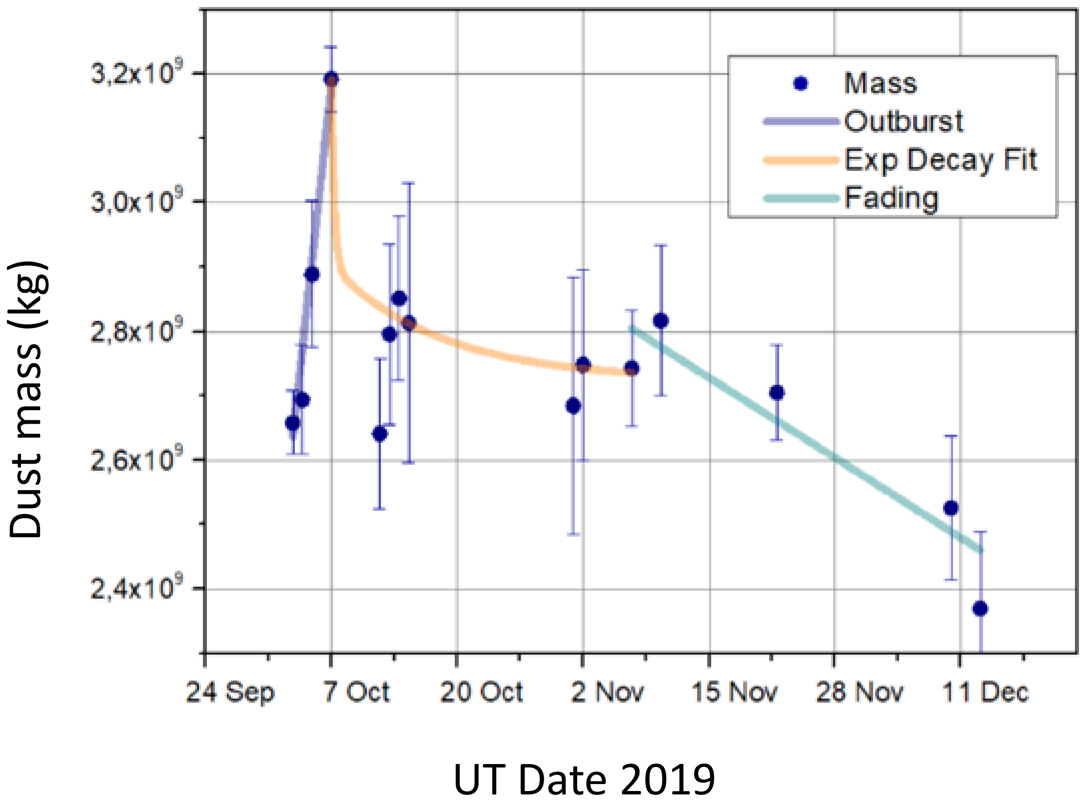


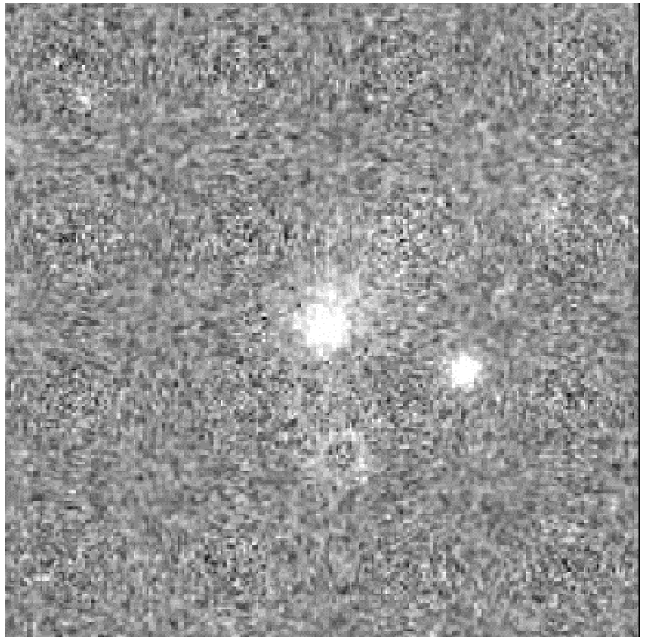
Table 3: Dust production properties for 2I/Borisov during pre-perihelion stage

Mass of dust ejected during the mini-outburst	5.3 ± 1.0 ($\times 10^8$ kg)
Dust production range	197 – 266 kg/s
Dust production peak	7 Oct 2019
Relaxation half-life	4.6 ± 2.3 days
Mass loss	-110 ± 30 kg/s

Conclusions and further work

Conclusions

- The comet is ejecting dust having a tail of approximately $40R_{\oplus}$ (2 Nov 2019)
- The profile indicates that 2I is a diffuse object, typical for a Solar System comet.
- The brightness starts to decrease, in the middle of November, 2 weeks before the perihelion passage
- Color indices suggest that 2I/Borisov is a reddish comet that resembles with the active comets and Trans-Neptunian objects of our solar system.



Animation: First attempts in correcting the overlap of the background sources

Further work

- Processing the remaining nights
- Propose a solution for saving the frames in which there is an overlapping with background sources