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Detection of a Water Tracer in Interstellar Comet 2I/Borisov

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Abstract

We present high spectral resolution optical spectra obtained with the ARCES instrument at Apache Point Observatory showing detection of the [O I] 6300 Å line in interstellar comet 2I/Borisov. We employ the observed flux in this line to derive an H_2O production rate of $(6.3 \pm 1.5) \times 10^{26}$ mol s^{-1}. Comparing to previously reported observations of CN, this implies a CN/H_2O ratio of ~0.3%–0.6%. The lower end of this range is consistent with the average value in comets, while the upper end is higher than the average value for solar system comets, but still within the range of observed values. C_2/H_2O is depleted, with a value likely less than 0.1%. The dust-to-gas ratio is consistent with the normal value for solar system comets. Using a simple sublimation model we estimate an H_2O active area of 1.7 km^2, which for current estimates for the size of Borisov suggests active fractions between 1% and 150%, consistent with values measured in solar system comets. More detailed characterization of 2I/Borisov, including compositional information and properties of the nucleus, is needed to fully interpret the observed H_2O production rate.

Unified Astronomy Thesaurus concepts: Comets (280); Astrochemistry (75); Planet formation (1241)

1. Introduction

Comets have a primitive volatile composition that is thought to reflect the conditions present in their formation region in the protosolar disk. This makes studies of cometary volatiles powerful for understanding the physical and chemical processes occurring during planet formation. However, observations to date only sample comets with a solar system origin. While the possibility exists that some comets with anomalous compositions such as 96P/Macholz (Langland-Shula & Smith 2007; Schleicher 2008) and C/2016 R2 (PanSTARRS; Biver et al. 2018; McKay et al. 2019) could have interstellar origins, the dynamics of these comets do not provide conclusive proof that they originate from a star system other than our own.

The discovery of interstellar comet 2I/Borisov provides an opportunity to sample the volatile composition of a comet that is unambiguously from outside our own solar system, providing constraints on the physics and chemistry of other protostellar disks. So far the only volatile that has been conclusively detected in Borisov is CN, with upper limits reported for C_2 (Fitzsimmons et al. 2019; Kareta et al. 2019), C_3, and OH (Opitom et al. 2019), and constraints on C_2 showing it is likely depleted compared to solar system comets. As H_2O is the dominant volatile in most solar system comets, measuring the H_2O production in Borisov is key for interpretation of all other observations of this comet, including other volatiles.

The [O I] 6300 Å line can be used as a proxy for the H_2O production rate in comets (e.g., Morgenthaler et al. 2007; Fink 2009; McKay et al. 2018). This line is a forbidden transition whose upper state is most efficiently populated when O I is released into the coma in the ^{1}D state after photodissociation of a parent molecule. In cometary comae for the ^{1}D state, this parent molecule is usually H_2O. We present observations of the [O I] 6300 Å line in Borisov and employ these observations to provide a measure of the H_2O production rate.

2. Observations and Analysis

We obtained spectral observations of Borisov on UT 2019 October 11, using the ARCES instrument mounted on the 3.5 m Astrophysical Research Consortium (ARC) Telescope at Apache Point Observatory in Sunspot, NM. ARCES is a cross-dispersed, high spectral resolution spectrograph with continuous spectral coverage from 3500 to 10000 Å and a resolving power of $R \equiv \frac{\lambda}{\delta\lambda} = 31{,}500$. This high resolving power is necessary for observations of [O I] 6300 Å emission in order to separate the cometary line from the corresponding telluric feature (see Figure 1). More information about the ARCES instrument can be found elsewhere (Wang et al. 2003).

Details of the observations can be found in Table 1. We obtained two spectra with 1800 s exposure times at airmasses of 2.14 and 1.74. The slit was oriented lengthwise along the parallactic angle. We observed the fast-rotating A star HD 80613 to serve as a telluric standard and HR 3454 for flux calibration of the spectra. Both were observed at airmass ~2.0, similar to the airmass of the Borisov observations. Hyades 64 was also observed as a solar standard for removal of solar absorption features, but due to the extremely weak nature of the continuum in the spectra of Borisov and the absence of any detectable absorption features we decided not to apply our solar standard to the cometary observations. We obtained observations of a quartz lamp for flat-fielding and a ThAr lamp for wavelength calibration. Spectra were reduced using an IRAF script that performs bias subtraction, flat-fielding, cosmic-ray removal, spectral extraction, and wavelength calibration. More details of our reduction procedures for cometary ARCES data can be found in McKay et al. (2012, 2014). After reduction and calibration, we coadded the two cometary spectra to increase signal to noise.

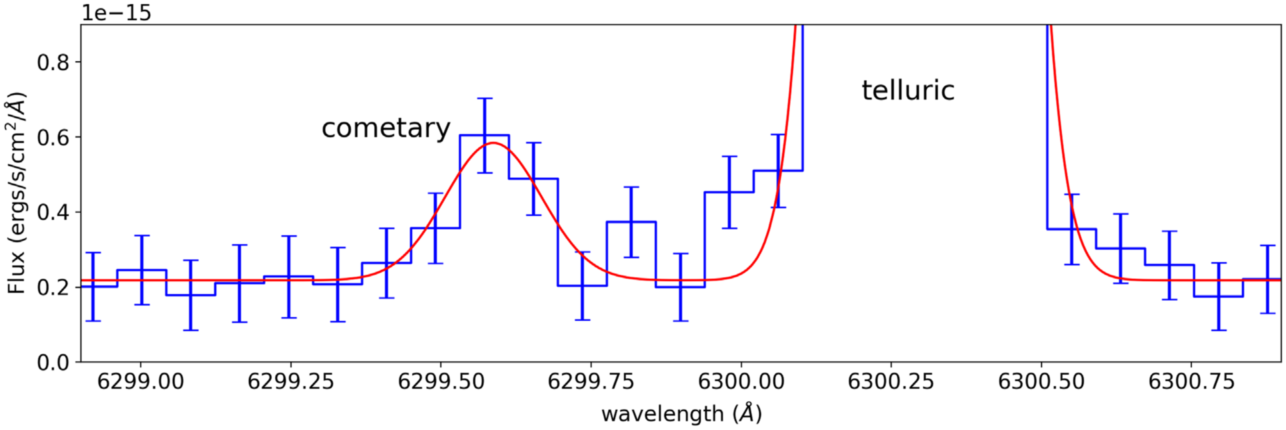

Figure 1. Spectral region showing the [O I] 6300 Å line in Borisov for our coadded spectrum (1 hr total on-source integration time). The telluric feature extends off the top of the plot, with the cometary line being the weaker feature blueward of the telluric line. The red line shows Gaussian fits to both the cometary and telluric features. These spectra do not have the continuum removed, so the continuum level was also a fitting parameter. Error bars represent $\pm 1\sigma$ uncertainties.

ARCES has a small slit ($3.2 \times 1\overset{''}{.}6$). Therefore, we accounted for slit losses from our flux standard using aperture photometry on our slit-viewer images and the methodology of McKay et al. (2014). For these observations slit losses add a systematic uncertainty in the derived flux of 12%.

We retrieved the observed flux by fitting a Gaussian to the line profile and calculating the corresponding flux. This flux is then used in a Haser model that includes modifications that emulate the vectorial formalism (Festou 1981) and also accounts for collisional quenching of the [O I] 6300 Å line emission. More details of this model can be found in McKay et al. (2012, 2014).

3. Results and Discussion

Figure 1 shows our detection of the [O I] 6300 Å line in Borisov, with a fit to both the cometary and telluric lines overplotted in red. As the continuum baseline was not removed during reduction, we included the continuum level as an additional parameter during the Gaussian fitting process. The cometary line is detected at the 5.0σ level. Assuming that H_2O is the dominant source of the [O I] 6300 Å line emission, we derive an H_2O production rate of $(6.3 \pm 1.5) \times 10^{26}$ mol s^{-1}. The uncertainty is dominated by photon statistics in the spectra rather than by the uncertainty in flux calibration. While our spectra cover other species of interest such as CN and C_2, no other emissions were detected and the upper limits derived from our observations would not provide more sensitive constraints than those already reported (Fitzsimmons et al. 2019; Kareta et al. 2019; Opitom et al. 2019).

Opitom et al. (2019) report an upper limit on the OH production rate (another proxy for H_2O production) of 2.0×10^{27} mol s^{-1}. Our [O I] 6300 Å line detection is consistent with this upper limit. While this manuscript was in review, Crovisier et al. (2019) reported a tentative water production rate of $(3.3 \pm 0.9) \times 10^{27}$ mol s^{-1} based on observations of the 18 cm OH line with the Nançay radio telescope coadded from 15 hr of observations obtained over a period of three weeks. This value is a factor of five higher than our value. Possible reasons for this discrepancy are discussed at the end of this section.

Fitzsimmons et al. (2019), Kareta et al. (2019), and Opitom et al. (2019) report detections of the CN molecule in the coma of Borisov. Using their measured CN production rates for the most contemporaneous observations, our H_2O production rate implies a CN/H_2O ratio of $0.59\% \pm 0.15\%$ (Fitzsimmons et al. 2019), $0.26\% \pm 0.06\%$ (Kareta et al. 2019), or $0.33\% \pm 0.08\%$ (Opitom et al. 2019). The CN mixing ratio derived from the Fitzsimmons et al. (2019) CN production rate is higher than the mean value of solar system comets measured to date (A'Hearn et al. 1995; Cochran et al. 2012), but still within the range of values found for solar system comets. The CN values from Opitom et al. (2019) and Kareta et al. (2019) give CN/H_2O ratios consistent both with each other and the mean value for solar system comets. As the measurements of Opitom et al. (2019) and Kareta et al. (2019) are the most contemporaneous with our measurements (closest observation dates are UT October 13 and UT October 10, respectively), perhaps these observations provide the most relevant comparison in accounting for possible variability in outgassing. We graphically compare the CN/H_2O ratio in Borisov to the sample of observed comets in A'Hearn et al. (1995) in the left panel of Figure 2.

For C_2, the upper limit from Fitzsimmons et al. (2019) combined with our result gives $C_2/H_2O < 0.63\%$, consistent with the mean value for solar system comets. Using the upper limits from Opitom et al. (2019) and Kareta et al. (2019) results in $C_2/H_2O < 0.1\%$ and $<0.03\%$, respectively, which is depleted compared to solar system comets (A'Hearn et al. 1995; Cochran et al. 2012). We include a graphical comparison of the C_2/H_2O ratio in Borisov to the sample of observed comets in A'Hearn et al. (1995) in the right panel of Figure 2. More observations are needed as Borisov approaches perihelion in order to provide a more definitive measure of its C_2 abundance.

Fitzsimmons et al. (2019) calculated an $Af\rho$ parameter, which serves as a proxy for dust production, of 143 ± 10 cm from their observations. Opitom et al. (2019) determined a very similar number. Using our measured H_2O production rate results in a $\log(Af\rho/Q_{H_2O})$ value of -24.6, which is similar to solar system comets observed at heliocentric distances similar to these observations ($\sim$2.5 au; A'Hearn et al. 1995). Jewitt & Luu (2019) calculated from photometric observations and a dust model that the dust mass-loss rate is approximately 2 kg s^{-1}, while Fitzsimmons et al. (2019) derived a value of 1 kg s^{-1}. Converting our H_2O production rate to mass results in an H_2O mass-loss rate of $\sim$19 kg s^{-1}. This is about a factor of three smaller than the rate calculated by Jewitt & Luu (2019)

Table 1
Observation Log

UT Date	R_h (au)	$\dot{R}_h$ (km s^{-1})	Δ (au)	$\dot{\Delta}$ (km s^{-1})	Solar Standard	Tell. Standard	Flux Standard
2019 October 11	2.38	−20.5	2.81	−34.2	Hyades 64	HD 80613	HR 3454

and Fitzsimmons et al. (2019) using the Fitzsimmons et al. (2019) CN production rate and assuming a typical CN/H_2O ratio for solar system comets. Our result that CN is enhanced in Borisov (at least when the Fitzsimmons et al. 2019 CN production rate is employed) compared to the mean CN/H_2O ratio in solar system comets explains this discrepancy. This is also supported by the fact that if the CN production rate from Opitom et al. (2019) or Kareta et al. (2019) is adopted (which compared with our H_2O production rate suggests a more typical CN/H_2O ratio), the inferred H_2O mass-loss rate is ∼30 kg s^{-1}, in better agreement with our value based on direct detection of a water tracer. Therefore, we conclude that the gas mass-loss rate is about an order of magnitude larger than the dust mass-loss rate, which would make Borisov incredibly gas-rich compared to the average solar system comet, but similar to gas-rich endmembers like 2P/Encke (A'Hearn et al. 1995). However, it should be noted that dust mass-loss rates are extremely model dependent, and Fitzsimmons et al. (2019) noted that using 20 μm grains instead of 1 μm grains resulted in a dust mass-loss rate of ∼30 kg s^{-1}, which would imply a dust-to-gas mass ratio closer to unity, consistent with the average value in solar system comets.

It is important to note that our observations are not simultaneous with those of Fitzsimmons et al. (2019) and Jewitt & Luu (2019), so any variability in the outgassing behavior of Borisov would complicate interpretation of these mixing ratios. In general, these previously reported observations were at larger heliocentric distance, where it would be expected that gas/dust production would be less. Therefore, it is possible that the CN, C_2, and dust production concurrent with our observations may be larger than the numbers reported for earlier observations, meaning all mixing ratios may be somewhat higher. However, the Opitom et al. (2019) and Kareta et al. (2019) observations bracket ours and show a fairly constant CN production rate over this time period, so as mentioned earlier perhaps these observations provide the most relevant comparison to our observations.

We use a simple sublimation model based on Cowan & A'Hearn (1979) in order to convert our measured H_2O production rate into an active area. We assume properties typical of solar system comets: low thermal inertia (justifying the slow rotator approximation, where every facet of the nucleus surface is in thermal equilibrium with the solar radiation incident upon it) and an albedo of 0.04. We also assume a spherical nucleus for simplicity. With these parameters we find an active area of 1.7 km^2. Using the derived radius upper limit of 3.8 km from Jewitt & Luu (2019) results in a lower limit on the active fraction of ∼1%, consistent with solar system comets (Sosa & Fernández 2011; Lis et al. 2019). However, Jewitt & Luu (2019) argue that the nucleus is likely much smaller than this, perhaps only a few hundred meters in radius. Jewitt et al. (2020) using *Hubble Space Telescope* observations come to a similar conclusion, constraining the nucleus size to 200–500 m in radius. For a 300 m body, our simple sublimation model implies an active fraction of 140%, which would imply a hyperactive nucleus. This phenomenon has been observed for solar system comets (A'Hearn et al. 2011; Lis et al. 2019) and is often explained as resulting from an extended source of H_2O-rich ice grains being released into the coma. Fitzsimmons et al. (2019) estimated based on their modeling efforts that the nucleus is 0.7–3.3 km in radius, resulting in active fractions of ∼1%–25%, similar to solar system comets. It must be noted, however, that our sublimation model uses a very simple treatment that is sensitive to thermal properties of the nucleus and albedo, which are not well constrained for Borisov. A more detailed modeling approach is beyond the scope of this Letter, but would be very beneficial for understanding the properties and activity of Borisov.

A possible complication in interpretation of the observed [O I] 6300 Å emission is that other volatiles such as CO, CO_2, and O_2 may contribute significantly to the emission if they are present at levels equal to or more abundant than H_2O. A recent example of this is C/2016 R2 (PanSTARRS), for which CO_2 was 30 times more abundant and CO was 300 times more abundant than H_2O, respectively, and it was determined that CO and CO_2 were the dominant contributors to the observed [O I] 6300 Å line flux (McKay et al. 2019). A possible way to constrain the contribution of CO and CO_2 to the [O I] population is through observations of the [O I] 5577 Å line (Festou & Feldman 1981; Bhardwaj & Raghuram 2012; McKay et al. 2012; Decock et al. 2013). While our spectra cover this feature, it was not detected and the upper limit on the flux ratio of the [O I] 5577 Å and [O I] 6300 Å lines of ∼1.0 is not sensitive enough to rule out CO and CO_2 as major contributors to the observed [O I] 6300 Å line flux. However, modeling of the dust coma by Jewitt & Luu (2019) suggests that activity began at a heliocentric distance of 4.5 au, much closer to the Sun than would be expected if CO_2 or CO was a dominant driver of activity and more consistent with H_2O sublimation. If confirmed, the tentative detection of OH using the Nançay radio telescope and the derived H_2O production rate (Crovisier et al. 2019) would provide additional evidence that the [O I] 6300 Å emission we observe does originate from H_2O photodissociation and therefore is an accurate tracer for H_2O. Observations of CO_2 at IR wavelengths and CO at either IR or submillimeter wavelengths are important for ruling out these potential contributors to the observed [O I] 6300 Å line flux.

As stated earlier, during review of this manuscript Croviser et al. announced in a CBET a tentative water production rate approximately five times larger than our reported value. While the brief nature of the CBET precludes a detailed comparison, we discuss some possible reasons for this discrepancy. At the high airmass of these observations and the small dimensions of the ARCES slit, differential refraction can result in wavelength-dependent slit loss, which can skew flux measurements. However, this is not expected for [O I] 6300 Å emission because this feature is close to the guiding wavelength (∼5500 Å). We confirmed that this is indeed negligible for [O I] 6300 Å emission based on observations of comet C/2012 S1 (ISON) that were performed at a similarly high airmass with

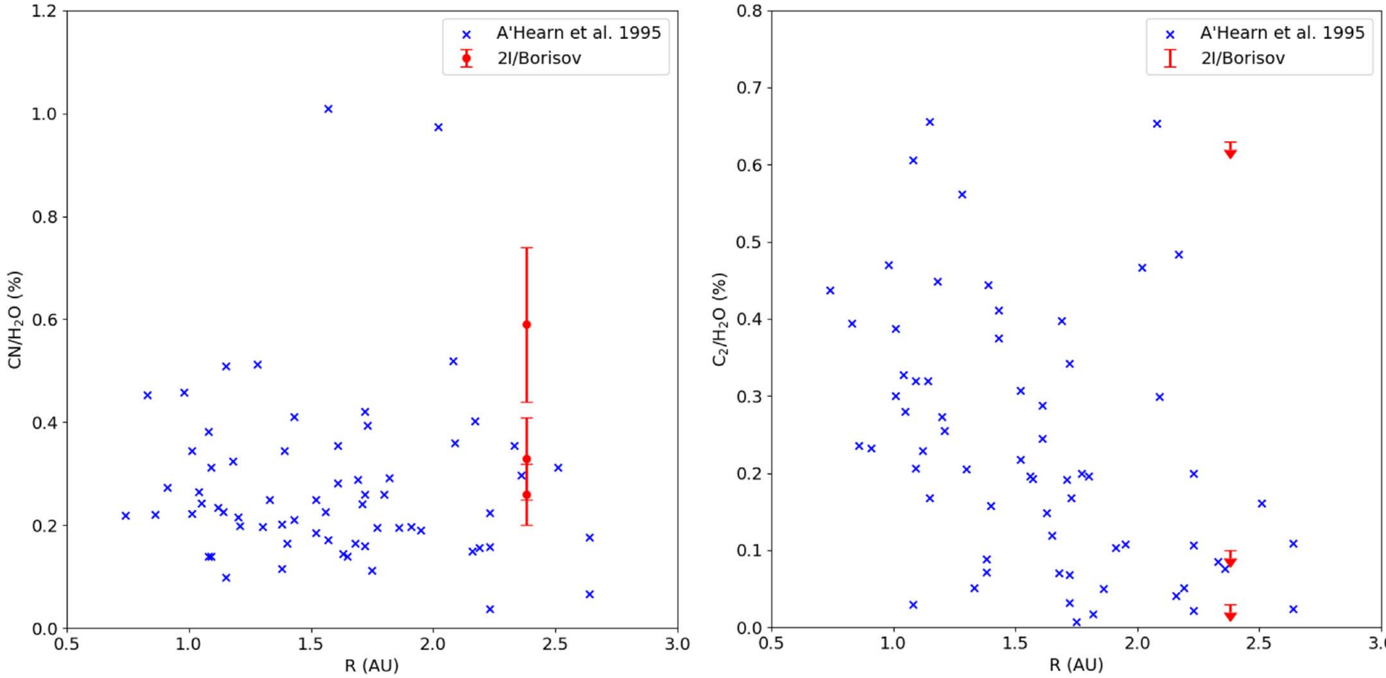

Figure 2. Left: CN/H_2O ratio in comets observed by A'Hearn et al. (1995) (blue crosses) as a function of heliocentric distance, with results for Borisov overplotted in red. As A'Hearn et al. (1995) report CN/OH ratios, we have converted to CN/H_2O using the relation from Cochran & Schleicher (1993). The values based on the measurements by Kareta et al. (2019) and Opitom et al. (2019) show values consistent with the mean value for solar system comets and other comets observed at this heliocentric distance, while the ratio based on the Fitzsimmons et al. (2019) measurement suggests a higher than average abundance, but still within the observed range for solar system comets. Right: same as the left panel, but for C_2/H_2O. The same conversion from C_2/OH to C_2/H_2O as for CN was performed. All values are upper limits, but the most sensitive values suggest Borisov is depleted in C_2.

ARCES, and found that the production rates derived from the ISON [O I] 6300 Å measurements were consistent with values determined using other methods (McKay et al. 2018). Therefore, we do not consider this or other airmass-dependent phenomena as the reason for the discrepancy. At certain geocentric velocities the cometary [O I] 6300 Å emission sits on top of a strong telluric absorption, and at high airmass inaccurate removal of this feature can result in a decrease in the measured flux and therefore production rate. This was observed for C/2012 S1 (ISON) (McKay et al. 2018). However, the geocentric velocity of 2I/Borisov during our observations was ~ -35 km s^{-1}, while the effect on observed [O I] 6300 Å line fluxes in comet ISON was only observed at geocentric velocities of ~ -50 km s^{-1}. Therefore, this is also not a likely candidate to explain the discrepancy. It is also possible that the activity is highly variable, and we observed Borisov at a minimum in activity, while the Nançay observations, which were coadded over three weeks of observations, provide a long-term average production rate. However, no such variability is observed for CN, with the CN production rate being fairly constant over a several week period (Kareta et al. 2019; Opitom et al. 2019).

The presence of an extended source of H_2O production, usually explained by the presence of water-rich icy grains in the coma, could account for the discrepancy. The main evidence for an extended source of H_2O production in cometary comae from ground-based observations is a dependence of derived production rates on the projected area of sky (aperture size) over which the production rate is measured. This phenomenon was observed for comet C/2009 P1 (Garradd) (Combi et al. 2013; Bodewits et al. 2014; McKay et al. 2015), with production rates measured with larger aperture sizes giving larger values than smaller apertures. The Nançay beam size is very large ($3\farcm5 \times 18'$), nearly 50,000 times larger than the projected area of sky covered by the ARCES slit! Therefore, any water sublimation from an extended source of icy grains could be missed by the ARCES observations but would be captured by Nançay, explaining the larger production rate measured by Nançay. The factor of five discrepancy is similar to the discrepancy observed for C/2009 P1 (Garradd) between narrow-slit and wide-field observations at a similar heliocentric distance (Combi et al. 2013; McKay et al. 2015). The Opitom et al. (2019) upper limit on the OH production of 2.0×10^{27} mol s^{-1} is also inconsistent with the reported tentative Nançay detection. Optitom et al. used a narrow-slit spectrometer ($2'' \times 8''$) with a field of view much smaller than the Nançay observations, and so their observation is also consistent with an extended source of water production outside the slit of Opitom et al. (2019) but inside the field of view of Nançay. If 2I/Borisov is indeed hyperactive as suggested earlier, an extended source of water production would be expected. Adopting the Crovisier et al. water production rate would increase our active fractions by a factor of five, making it quite likely that Borisov would have to be hyperactive to explain their observations. However, a full comparison of the different constraints on water production will have to await publication of the Nançay results. Additional measurements/constraints on water production are also needed to confirm or refute the hypothesis of an extended source of water production and hyperactivity.

4. Conclusions

We present spectra showing detection of [O I] 6300 Å emission in interstellar comet 2I/Borisov. This provides the first measurement of the H_2O production rate in this very intriguing object. We determined an H_2O production rate of $(6.3 \pm 1.5) \times 10^{26}$ mol s^{-1}, which when compared to CN measurements suggest Borisov is either enhanced or typical in CN compared to the average value for solar system comets, though the enhanced numbers are still within the range of observed values. C_2 is depleted compared to H_2O. The dust-to-gas ratio based on $Af\rho$ and dust mass estimates are consistent with solar system comets. Using a simple sublimation model, we find an H_2O active area of 1.7 km^2, which for current constraints on the nucleus size could imply active fractions from as low as 1% to >100% (implying a hyperactive nucleus), though these active fractions are highly model dependent. More measurements are needed as Borisov approaches perihelion to fully understand its composition and activity.

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