LETTER TO THE EDITOR

Size and albedo of the largest detected Oort-cloud object: comet C/2014 UN\textsubscript{271} (Bernardinelli-Bernstein)

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ABSTRACT

Context. The recently announced Oort-cloud comet C/2014 UN\textsubscript{271} (Bernardinelli-Bernstein) is remarkable in at least three respects: (i) it was discovered inbound as far as \textsim 29 au from the Sun (with prediscovery images up to \textsim 34 au); (ii) it showed cometary activity already at almost 24 au; and (iii) its nuclear magnitude (H, \textsim 8.0) indicates exceptionally large object. Detection of gases is expected in the upcoming years as the comet is heading towards a \textsim 11 au perihelion in 2031.

Aims. The goal is to determine the object’s diameter and albedo from thermal measurements.

Methods. We used ALMA in extended configuration (resolution \textsim 0.06\arcsec) to measure the 1287 \textmu m (233 GHz) continuum flux of the comet. Observations were performed on August 8, 2021 at a 20.0 au distance from the Sun. The high spatial resolution was chosen in order to filter out any dust contribution. We also used a recently published A\textsubscript{fp} value to estimate the dust production rate and the expected dust thermal signal for various assumptions on particle size distribution.

Results. We detected the thermal emission of the object at \textsim 10 \sigma, with a flux of 0.128\pm0.012 mJy. Based on observational constraints and our theoretical estimates of the dust contribution, the entirety of the measured flux can be attributed to the nucleus. From NEATM modelling combined with the H magnitude, we determine a surface-equivalent diameter of 137\pm1 km and a red geometric albedo of 5.3\pm1.2 \%. This confirms that C/2014 UN\textsubscript{271} is by far the largest Oort-cloud object ever found (almost twice as large as comet C/1995 O1 Hale-Bopp), and except for the Centaur 95P/Chiron which shows outburst-like activity, the largest known comet in the Solar System. On the other hand, the C/2014 UN\textsubscript{271} albedo is typical of comets, adding credence for a “universal” comet nucleus albedo.

Conclusions. With its distant perihelion and uniquely large size, C/2014 UN\textsubscript{271} (Bernardinelli-Bernstein) is the prominent archetype of distant comets, whose activity is driven by hypervolatiles. Monitoring of dust and gas emission as the comet will approach and pass perihelion will permit to study its activity time pattern and compare it to the distant (outbound) activity of Hale-Bopp. Post-perihelion thermal measurements will permit to study possible albedo changes, such as a surface brightening compared to pre-perihelion, as was observed for Hale-Bopp.

Key words. Comets, Comets:individual: C/2014 UN\textsubscript{271} (Bernardinelli-Bernstein)

1. Introduction

Comet C/2014 UN\textsubscript{271} (Bernardinelli-Bernstein) (hereafter 2014 UN\textsubscript{271} for brevity) was discovered as part of the search for outer solar system objects with the Dark Energy Survey (DES) performed over 2013–2019 (Bernardinelli et al. 2021b). 2014 UN\textsubscript{271} was observed in 42 DES survey images on 25 nights over Oct. 2014 – Nov 2018, with a heliocentric distance \textsim 29 au (Bernardinelli et al. 2021b). Prediscovery images from WISE, CFHT, VST, VISTA and PanSTARRS extend the photometric record to Oct. 2010 (\textsim 34.1 au). Orbital analysis (Bernardinelli et al. 2021b) indicates characteristic Oort-cloud membership, with inclination and semi-major axis of the incoming orbit of 95.5\degree and 20,200 au respectively (i.e., an inbound orbital period of \textsim 2.9 million years). The object is heading towards a 10.95 au perihelion passage on 21 Jan. 2031. Backward orbit integration points to a previous perihelic passage at 17-21 au, and suggests that 2014 UN\textsubscript{271} has never been closer than this distance since its ejection from the Oort cloud, possibly making it one of the most ‘pristine’ comets ever observed.

The announcement of the object on 19 June 2021 (Bernardinelli & Bernstein 2021) prompted immediate observations, that showed a visible coma at \textsim 20.18 au (Demetz et al. 2021; Kokotanekova et al. 2021; Buzzi & Lister 2021). Analysis of TESS data from Sept.-Oct. 2018 indicated that a coma was already present at 23.8 au, and syndyne analysis suggested the activity might have started several years earlier (Farnham et al. 2021). 2014 UN\textsubscript{271} thus joins the list of inbound, distantly active, long-period comets, that includes C/2017 K2 (PanSTARRS), C/2010 U3 (Boattini), and C/2014 B1 (Schwartz). Also, comet C/1995 O1 Hale-Bopp was observed to be active outbound 11 years after perihelion at 25.7 au from the Sun (Szabó et al. 2008), and may be even at 30.7 au (Szabó et al. 2011). Activity in these objects may in fact occur even farther: modelling of the \textsubscript{r_h} dependence of the dust production rate in C/2017 K2 indicates activity was already present at 35 au, presumably driven by the sublimation of CO or other supervolatile ices (Jewitt et al. 2021).

Of further interest for the characterization of 2014 UN\textsubscript{271} are the following aspects (Ridden-Harper et al. 2021; Farnham et al. 2021; Bernardinelli et al. 2021b).
Table 1. Observation parameters

| Scheduling block | UT Date (start/end) | Integration time | Flux calibrator and flux density$^d$ | Phase calibrator and flux density$^b$ | 2014 UN$^{271}$ Flux density$^b$ |
|------------------|---------------------|------------------|-------------------------------------|-------------------------------------|---------------------------------|
| SB1              | 08-Aug-2021 7:37 - 8:35 | 1624 sec         | J2258-2758 1.22 Jy                  | J0253-5411 0.374 Jy                  | 0.109±0.016 mJy -0.091" -0.249" |
| SB2              | 08-Aug-2021 8:35 - 9:30 | 1613 sec         | J0519-4546 1.26 Jy                  | J0253-5411 0.389 Jy                  | 0.147±0.016 mJy -0.100" -0.262" |

$^a$ Assumed; $^b$ Measured; $^c$ (RA, DEC) offset with respect to predicted position. Adopting a mean (-0.0955", -0.2555") offset for the two SBs, the J2000 astrometric coordinates with respect to the observing site (Code -7) on August 8, 2021, UT = 8:00 are: RA = 02:42:04:2508 and DEC = -53:26:48.520.

Kokotanekova et al. [2021]: (i) possible fluctuations of the magnitude, but a lack of a clear rotational signal at the > 0.2-0.3 mag level; (ii) a moderately red color, with spectral slope 5-10 % / 100 nm, typical of (or slightly bluer than) long-period comets (Jewitt 2015). Gas emissions have not been detected yet, with production rates $Q_{CO} < 1.25\times10^{28}$ mol s$^{-1}$ and $Q_{CN} < 1.25\times10^{25}$ mol s$^{-1}$ near $\sim$21 and $\sim$20 au respectively (Farnham et al. [2021], Kokotanekova et al. [2021]). Most remarkable for 2014 UN$^{271}$ is however its exceptionally bright absolute magnitude $H_r = 7.96\pm0.03$, which showed no evolution in ground-based data during the approach from 34 to 22 au and therefore presumably represents the nuclear magnitude (Bernardinelli et al. [2021]). For a standard cometary 5 % red albedo, and based on usual relationships between diameter $D$ and $H$ magnitude (see Sect. 3.2), this yields $D = 130$ km, potentially 1.75 times larger than Hale-Bopp (74±6 km diameter, Szabó et al. [2012]). 2014 UN$^{271}$ would thus compete in size with the largest Centaurs and with the smallest of the TNOs having size measurements, whose typical (visible) albedos are however more like 8 % (Müller et al. [2020]).

Fig. 1. Recentered 233 GHz total image of 2014 UN$^{271}$ merging data from the two SBs and the four spectral windows. The synthesized beam, shown in white, is 0.067"×0.062". The scale of the color bar is in mJy.

2. Observations and data reduction

Observations of comet C/2014 UN$^{271}$ were obtained on August 8, 2012, with the 12-m array of the Atacama Large Millimeter Array (ALMA), under the ALMA DDT project 2019.A.00038 (see details in Table 1). Heliocentric distance, geocentric distance, and phase angle values of the target were $r_h = 20.0046$ au, $\Delta = 19.6776$ au and $\alpha = 2.77^\circ$, respectively. All observations were taken in the ALMA Band 6 (211-275 GHz), in the continuum ("TDM") mode. We used the standard frequency tuning for that band, yielding four 1.875-GHz broadband spectral windows centered at 224, 226, 240 and 242 GHz. The array was in extended configuration C8, with 40 operating antennas. This yielded baselines in the range 92m – 8282m, and a synthesized beam of $\sim$0.065" for robust weighting (0.5), larger than the expected nucleus size (~10 mas) but allowing to filter out dust emission. Observations were obtained in dual polarization mode, with the two polarizations combined at data reduction stage to provide a measurement of the total flux.

The observations consisted of two scheduling blocks (SB), each ~55-58 min long including ~27 min on source. The rest of the time in each scheduling block was spent on flux/bandpass calibrators, and on secondary (phase) calibrators for monitoring the atmospheric and instrumental amplitude and phase gains. Observations occurred in excellent weather conditions (zenithal precipitable water vapor ~ 0.9 mm; antenna-based phase rms ~ 26 degrees). Observational details and flux results are given in Table 1.

The flux/bandpass calibrators, namely quasars J0519-4546 and J2258-2758 for the two SBs, are actually variable, but routinely monitored. Details on how we estimated their flux and associated error bar on the observing date are given in Appendix A.

Initial steps of the data reduction were performed in the CASA reduction package via the ALMA pipeline (Muders et al. 2014), providing a set of visibilities as a function of baseline between each antenna pair. Visibility fitting was performed for the two flux calibrators, and visibilities were rescaled (by factors...
0.99 and 0.995 for SB1 and SB2, respectively, from the ALMA pipeline calibration) so that their measured flux matched the values expected from Appendix A (and recalled in Table 1). These factors were also applied to visibility data of the phase calibrator (J0253-5441) and of the science target. Visibility fitting provided two independent values of the flux of J0253-5441, found to be consistent within 4 % (see Table 1), confirming the quality of the flux scale.

For 2014 UN271, visibilities were exported into the GILDAS package for imaging and visibility fitting. Combining data from the two SBs and the four spectral windows, a 233-GHz image of C/2014 UN271 is shown in Fig. 1 yielding a detection of the object at ~ 10 σ. Visibility fitting was performed independently for the two SB. In a first step, for each SB, each of the four spectral windows yielded a measure of the flux and of the (RA, DEC) position offset of the target from the expected ephemeris, letting these parameters free in the fit and specifying a point-like source. The four sets of (RA, DEC) values were then kept fixed at their average values (see Table 1), and the visibilities were refit in terms of the object total flux. We specified either a point-like source or a 9.5 milli-arcsec (mas) disk (which corresponds to the a posteriori determination of the object diameter), with insignificant differences (~ 0.001 mJy in flux). For each SB, the combined 233 GHz flux and its error bar were obtained by merging the visibilities from the four spectra windows (GILDAS task uv_merge), after rescaling to that frequency using a spectral index $\alpha = d(\log F_\nu)/d(\log \nu) = 1.93$ in the 224-242 GHz range, as expected from NEATM models (see Sect. 3.3), and performing again visibility fitting. This yielded 0.109±0.016 mJy for SB1 and 0.147±0.016 mJy for SB2, i.e. a somewhat unexpected 2.4-σ difference. In theory, the object’s thermal flux might show rotational variability associated with a triaxial ($a, b, c$) projected shape, but even assuming the two SB were precisely in phase with projected surface maxima and minima, the 35 % higher flux in SB2 would strictly imply $a > 1.8$. This is also at face value inconsistent with the lack of rotational variability at the >0.2-0.3 magnitude level in optical data, although the latter might be damped by coma contribution. In what follows, we simply averaged the fluxes from the two SB, yielding 0.128±0.011 mJy \textsuperscript{1}. Quadratically adding a conservative 4 % uncertainty on the flux calibrator scale, the final object flux is 0.128±0.012 mJy.

3. Analysis

3.1. Estimate of coma contribution

Visibility curves $V$ as a function of UV radius $\sigma$ bear information on the spatial distribution of the source. For a uniform disk of apparent diameter $\theta$, $V(\sigma)$ follows a $J_1$ Bessel function, with first zero at $\sigma_0 = 1.22 \lambda/\theta$, and a constant value for a point-like source. Extended emission for a coma brightness distribution varying as $1/\sigma$, where $\rho$ is the distance to the comet center, shows up as visibilities $V(\sigma) \sim 1/\sigma$ (Bockelée-Morvan et al. 2010). Fig. 2 shows the real part of the observed visibilities for 2014 UN271, weight-averaged in 400-m wide $\sigma$ bins, the latter being plotted in terms of $\lambda$. From $\chi^2$ analysis, visibility fitting cannot distinguish between disk sizes smaller than ~40 mas, which is to be expected given the ~65 mas resolution achieved and the measurements’ S/N. Most importantly, within noise level, no indication of a 1/σ signal component is apparent. Fitting the $V(\sigma)$ curve with the sum of a constant and a 1/σ term provides no better fit than the previous point-like and < 40 mas disk models, and in this case (sixth model in Fig. 2, blue curve), the nucleus contributes 93 % of the signal. A 3σ upper limit to the contribution of the coma to the visibility at $\sigma = 270$ km (220 kA) can be set at the 0.1 mJy level (orange curves in Fig. 2). Even in this extreme case, the contribution of the nucleus is 0.097 mJy, i.e. 76 % of the total flux. This is a first, observational, proof of a dominant nuclear contribution to the signal.

Furthermore, based on the comet dust activity level reported on 29 June 2021 (Dekelver 2021; Bernardinelli et al. 2021b), i.e. an $A_F$ value of ~150 m, we estimated the expected thermal signal from the dust in the ALMA synthesized beam, for different assumptions of the particle size index ($b$) and maximum particle radius ($a_{\text{max}}$). Results, described in Appendix A, indicate that for most assumptions, the thermal emission of dust is entirely insignificant. Only if the particle size distribution is extremely shallow ($b = 3$) and the maximum particle size very large ($a_{\text{max}} = 1$ cm) is there a non-negligible dust contribution to the measured signal, but still minor and within the uncertainty of the measured visibilities. In the rest of the paper, the measured thermal flux of 0.128±0.012 mJy is attributed to the nucleus only.

3.2. Nucleus diameter and albedo

In the lack of knowledge of nucleus shape and spin parameters (pole orientation and shape), a thermophysical model is pointless, and we instead adopted a NEATM model, used extensively for asteroids (Harris 1998) and trans-neptunian objects (Müller et al. 2020 and references therein). NEATM is based on the asteroid standard thermal model (STM; Lebofsky & Spencer 1989), but accounts for phase angle effects; additionally, the temperature distribution is modified by an adjustable $\eta^{-1/2}$ factor, representing the combined and opposed effects of roughness ($\eta < 1$) and thermal inertia ($\eta > 1$). For fixed surface (thermal inertia, roughness) and spin properties, $\eta$ is also a function of the subso-

\textsuperscript{1} JPL/Horizons interrogated on July 14, 2021
\textsuperscript{2} This error bar is also satisfactorily consistent with $s盥de/\sqrt{b} = 0.013$ mJy where $s盥de$ is the standard deviation between the 8 individual flux values rescaled to 233 GHz.
lar temperature, i.e. the heliocentric distance (e.g. Spencer et al. 1989, Lellouch et al. 2013). Given the $r_0 = 20$ au distance of our measurements (and the expected large size of 2014 UN271), we adopted a beaming factor $\eta = 1.175 \pm 0.42$, based on measurements of 85 Centaurs and TNOs (Lellouch et al. 2013, 2017). We also specified a bolometric emissivity $\epsilon_b = 0.90 \pm 0.06$ and a relative radio emissivity $\epsilon_r = \epsilon_{mm} / \epsilon_b = 0.70 \pm 0.13$, as inferred from combined Spitzer/Herschel/ALMA measurements of 9 objects (Brown & Butler 2013, Lellouch et al. 2017). The lower-than-unity relative radio emissivity is interpreted as resulting from (i) the sounding of a colder dayside subsurface and (ii) the loss of outgoing thermal radiation due to volume scattering in the subsurface, and/or Fresnel reflection at the surface. The few available radio-observations of cometary nuclei also generally indicate radio-emissivities lower than 1, e.g. ~0.5 for Hale-Bopp (Fernández 2002), and <0.8 for 8P/Tuttle (Boissier et al. 2011). Comets are also found to have low thermal inertias (e.g., <10, <30 and <45 MKS for 8P/Tuttle, 22P/Kopff, and 9P/Tempel 1, respectively; Boissier et al. 2011; Groussin et al. 2009, 2013), consistent with a beaming factor $\eta$ of order unity. Based on NEATM analysis of a large sample of comet nuclei observed with Spitzer at $r_0 = 3.5$–6 au, Fernández et al. 2013 find a mean value of $\eta = 0.33 \pm 0.11$; and the large (D = 65 km) 29P/Schwassmann-Wachmann nucleus has $\eta = 1.1 \pm 0.2$ (Schambeau et al. 2021). These numbers are fully consistent with our above choice of $\eta$. Given the values of $r_0$, $\eta$, and $\epsilon_b$, NEATM calculations indicate that the object’s spectral index over 224-242 GHz is 1.93, slightly lower than the Rayleigh-Jeans limit of 2.

With the above parameters, the measured thermal flux yields the object’s (surface-equivalent) diameter $D$, and the albedo is then determined from the usual relationship between diameter $D$ and $H$ magnitude, i.e. $D = 2\alpha / \sqrt{\pi} 10^{0.25m_H-4}$. $\alpha$ is the object’s geometric albedo and $m_H$ the solar magnitude, in the relevant band, and $a = 1$ au. Using $V_0 = 22.586$ and $(V-R)_0 = 0.35$, one obtains $D = 1330$ km / $\sqrt{\pi} \ 10^{0.25m_H}$ from V band and $D = 1132$ km / $\sqrt{\pi} \ 10^{-2.21m_H}$ from R band. We converted the $(V, R)$ magnitudes and colors from Bernardinelli et al. 2019 using the prescriptions of Jester 2005, yielding $H_V = 8.21 \pm 0.05$, $H_R = 7.75 \pm 0.05$, and $V-R = 0.46 \pm 0.02$, i.e. $p_V = 1.11 \pm 0.02$ $p_V$. The temperature distribution $T$ across the object is also a function of the object’s albedo $p_V$ through $T = (1 - p_V q) / q$ (where a reasonable value of $q$, the phase integral, is ~0.4), but this dependence is minimal given the a posteriori low albedo inferred ($p_V \sim 0.049$), so iterating once on the albedo in NEATM was sufficient.

To account for uncertainties, both on the measured object’s flux and on the model inputs ($\eta$, $\epsilon_b$, $\epsilon_r$, and $H$), we randomly generated a large set (40,000) of synthetic data and model inputs, based on gaussian-added noise on each parameter at the appropriate level (Mueller et al. 2011), solving for $D$ and $p_V$ in each case. In doing so, we restricted $\eta$ values to be >0.6 (lower values are physically implausible, see Mommer 2012), as well as $\epsilon_b < 1$ and $\epsilon_r < 1$.

4. Results and discussion

Fig. 3 shows the distribution of the solution $D$ and $p_V$, accounting separately for flux uncertainties, model uncertainties, and both. Those provided best fit values and error bars (defined to include the central 68.3 % of the results) for the diameter and albedo. We find $D = 137 \pm 17$ km \footnote{This yields an apparent diameter of 9.6 mas at $\Delta = 19.68$ au, consistent with the point-like appearance of the object in the visibility curve (Fig. 2).} and $p_V = 5.4 \pm 1.2$ %, where error bars are dominated by model errors – and principally by the uncertainty on $\eta$. This confirms that 2014 UN271 is almost twice larger in diameter than Hale-Bopp and makes it the largest Oort Cloud comet detected so far. 2014 UN271 is also larger than almost all active Centaurs (e.g. D = 60 km for 167P/Cineos, 174P/Echeclus, and 29P/Schwassmann-Wachmann, see Müller et al. 2020, Schambeau et al. 2021), being surpassed only by 95P/Chiron (D = 215 km; Fornasier et al. 2013). Given however that Centaurs activity occurs mostly in the form of outbursts of variable lifetim\footnote{In the case of 29P, superimposed on a steady background activity level.} but is mostly uncorrelated with heliocentric distance (Peixinho et al. 2020, and references therein), 2014 UN271 appears as the largest “standard comet” ever discovered.

Unlike the size, the albedo of 2014 UN271, $p_V = 4.9 \pm 1.1$ %, is completely in line with that of other, typically much smaller, comets (2–6 % in V or R for a sample of ~80 elliptic or near-isotropic comets, with no discernible trends with other orbital or physical parameters, see Lamy et al. 2004, Campins & Fernández 2002). Our measurement thus adds evidence against a dependence of comet nucleus albedo on size. Such a conclusion was reached previously by Fernández et al. 2013 on the basis that the size distribution they measured for 89 comets in the thermal range is indistinguishable from that inferred from optical photometry assuming constant albedo. In this context, 95P/Chiron, with $p_V = 0.10-0.17$ (Lellouch et al. 2017), stands as a clear outlier both from comet nuclei and from the Centaur population as a whole (median $p_V$, 5.6 %; see Müller et al. 2020). We also note that with its ~5 % albedo and 5-10 % /100 nm spectral slope, 2014 UN271 falls in the middle of the “dark/neutral” cluster identified in the Kuiper Belt
The low albedos encountered on many outer solar system objects are usually associated with the presence of exposed organics, along with additional darkening agents like sulfides (Rousseau et al. 2018). This hypothesis is strengthened by the detection of large amounts (~50 % in mass) of organics in the dust of 67P/Churyumov-Gerasimenko (Bardyn et al. 2017), but many questions remain as to the relations between albedo, color, composition, irradiation, and activity (see e.g., Brunetto et al. 2006; Jewitt 2013; Poston, Mahouè & Ehlmann 2018; Wong, Mishra & Brown 2019).

Our observation at 20 au provides the most distant determination of the albedo of a new Oort Cloud object on its inbound orbit. This is of interest because cometary activity may cause the perihelion passage, due to the blowing-off surface layers (Fornasier et al. 2016; Filacchione et al. 2020).

Just as Hale-Bopp is the archetype of a large comet on a Sun-approaching orbit, 2014 UN271 appears as the most prominent representative of distant, long-period comets, whose activity is governed by hypervolatiles (CO, CO2,...), and monitoring of its chemical composition as it will approach and pass perihelion will permit to assess whether these processes occur as well on this comet.

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References
A'Hearn, M. F., Schleicher, D. G., Mills, R. L., et al. 1984, AJ, 89, 579.
Bardyn, A., Baklouti, D., Cottin, H., et al. 2017, MNRAS, 469, S712. doi:10.1093/mnras/stx2640
Biver, N., Bockelée-Morvan, D., Colom, P., et al. 2002, Earth Moon and Planets, 90, 5. doi:10.1023/A:1021599915018
Bernardini-Bernstein, P. H., & Bernstein, G. 2021, Minor Planet Electronic Circulars, 2021-M36
Bernardini-Bernstein, P.H., Bernstein, G.M., Sakot, M., et al. 2021a, 2021arXiv210903578B
Bernardini-Bernstein, P. H., Bernstein, Montet, B., et al. 2021b, ApJ, 921, L37. doi:10.3847/2041-8213/ac3d34
Biver, N., Bockelée-Morvan, D., Colom, P., et al. 2002, Earth Moon & Planets, 90, 323
Bockelée-Morvan, D., Boissier, J., Biver, N., & Crovisier, J. 2010, Icarus, 210, 1
Bockelée-Morvan, D., Rinaldi, G., Erard, S., et al. 2017, MNRAS, 469, S443. doi:10.1093/mnras/stx1950
Boissier, J., Grouiss, O., Jordà, L., et al. 2013, 19 A & A, 526, 7 pp.
Brown, M. E., & Butler, B. J. 2017, AJ, 159, 32
Brunetto, R., Barucci, M. A., Dotto, E., & Strazzulla, G. 2006, ApJ, 646, 646
Buzzi, L., & Lister, T. 2021, Minor Planet Electronic Circulars, 2021-M83
Campins, U., & Fernández, Y. 2002. Earth, Moon, and Planets, 117.
Crist, J. F. & Rodionov, A. V. 1997, Icarus, 127, 319. doi:10.1006/icar.1997.5690
Dekelver, P.-J. 2021, 2014 UN271 Bernardini-Bernstein, P.H. et al. 2021a, 2021arXiv210903578B
Demetz, L., Buzzi, L., Alletti, A., & Lister, T. 2021, Central Bureau Astronomical Telegrams, CBET-4099
Fink, U. & Rubin, M. 2012, Icarus, 221, 701. doi:10.1016/j.icarus.2012.09.001
Farnham, T. L., Kelley, M. S. P., & Baurer, J. M. 2021, PSJ, 2, 236. doi:10.3847/PSJ/ac3d34
Fernández, Y.R., 2002, Earth, Moon, & Planets, 89, 3
Fernández, Y.R., Kelley, M.S., Lamy, P., et al. 2013, Icarus, 226, 1138
Filacchione, G., Capacci, F., Ciarniello, M., et al., 2020, Nature, 578, 487
Fornasier, S., Lellouch, E., Müller, T. et al. 2013. A & A, 555, A51
Fornasier, S., Mortola, S., Keller, H-U. et al. 2016, Science, 354, 1566
Grouiss, O., Lamy, P., Toth, I. et al., 2009, Icarus, 199, 568
Grouiss, O., Sunshine, J. M., Feaga, L. M., et al., 2013, Icarus, 222, 580
Harris, A. W. 1998, Icarus, 131, 291
Jester, S., Schneider, D. P., Richards, G. T., et al. 2005, AJ, 130, 873
Jewitt, D. 2015, AJ, 150, 201
Jewitt, D. 2021, AJ, 150, 201
Keller, M. S. P., Lister, T., & Holt, C. 2021, Afid, 149171
Kokotanekova, R., Opitom, C., Knight, M., et al., 2021, Bull. Amer. Astron. Soc., 53, No. 1-e 2021abstrs04
Lacerda, P., Fornasier, S., Lellouch, E., et al., 2014, ApJL, 793L3 (6pp)
Lamy, P. L., Toth, I., Fernandez, Y. R., & Weaver, H. A. 2004, in Comets II, eds. M. C. Festou, H. U. Keller, & H. A. Weaver, 223
Lebofsky, L. A., & Spencer, J. R. 1989, in Asteroids II, ed. R. P. Binzel, T. Gehrels, & M. S. Matthews (Arizona University Press), 128
Lellouch, E., Santos-Sanz, P., Lacerda, P., et al., 2013, A & A, 557, A60
Lellouch, E., Santos-Sanz, P., Fornasier, S., et al. 2016, A&A, 588, A22.
Lellouch, E., Moreno, R., Müller, T. et al., 2017, A & A, 608, A45
Mestdagh, P., Marmott, M., Harris, A.W.K. Kiss, Cs., et al., 2012, A & A 541, A93
Muders, D., Wysocki, F., Lightfoot, J., et al., 2014, The ALMA Pipeline. In N. Manset and P. Forshay, editors, Astronomical Data Analysis Software and Systems XXII, May 2014.
Peixinho, N., Thouron, A., Tegler, S. C. et al., 2020, In "The trans-neptunian solar system", D. Prialnik et al., M.-A. Barucci, L.A. Youn, eds, pp. 153-181
Poston, M. J., Mahouè, A., & Ehlmann, B. L. 2018, ApJ, 856, 124
Rauer, H.; Hellert, J.; Arpigny, C., et al., 2003, A & A, 397, 1109
Hviden-Harper, R., Bannister, M. T., & Kokotanekova, R. 2021, RNASS AAS, 5, 161
Roth, N. X., Milam, S. N., Cordiner, M. A., et al. 2021, ApJ, 921, 14. doi:10.3847/1538-4357/ac0441
Rousseau, B., Erard, S., Beck, P. et al. 2018, Icarus, 306, 306

This paper is based on ALMA program 2019.A.00038. ALMA is a partnership of ESO (representing its member states), NSF (USA) and NINS (Japan), together with NRC (Canada), NSC and ASIAA (Taiwan), and KASI (Republic of Korea), in cooperation with the Republic of Chile. The Joint ALMA Observatory is operated by ESO, AUI/NRAO and NAOJ. The National

7 The nucleus of 67P also underwent bleaching and brightening during the perihelion passage, due to the blowing-off of volatile-depleted superficial layers and the exposure of brighter and bluer ice-rich sub-surface layers (Fornasier et al. 2018; Filacchione et al. 2020).

See Table A.1 for a list of abbreviations and symbols.
Schambeau, C. A., Fernández, Y. R., Samarasingha, N. H., et al. 2021, PSJ, 2, 126. doi:10.3847/PSJ/abf66f

Spencer, J. R., Lebofsky, L. A., & Sykes, M. V., 1989, Icarus, 78, 337

Stansberry, J. A., van Cleve, J., Reach, W. T. et al., 2004, ApJ Suppl. Ser., 154, 463

Szabó, Gy., Sárnezky, M., & Kiss, L. L., 2008, ApJ, 677, L121

Szabó, Gy., Sárnezky, M., & Kiss, L. L., 2011, A & A, 531, id.A11

Szabó, Gy., Kiss, L. L., Pál, A., et al., 2012, ApJ 761:8 (7pp)

Wong, I., Mishra, A., & Brown, M. E., 2019, AJ, 157, 225

Zakharov, V. V., Ivanovski, S. L., Crifo, J.-F., et al. 2018, Icarus, 312, 121. doi:10.1016/j.icarus.2018.04.030
Appendix A: Absolute flux calibration

A good knowledge of the calibrators is critical for the reliability of the flux scale. Our flux/bandpass calibrators, J2258-2758 and J0519-4546 for the first and second scheduling blocks (SBs) respectively, are actually variable, but routinely monitored from ALMA mostly at 91.5, 103.5, and ∼340 GHz (337.5 or 345.3 GHz), and for the second one occasionally at 233 GHz. These measurements are displayed in Fig. A1 over a ~100 day period spanning our observing period. We fitted the 91.5, 103.5, and ∼340 GHz fluxes with 5-degree polynomials, from which the spectral index over this frequency range and the 233 GHz flux was determined as a function of time. Interpolation on the date of our observation then yielded the desired quasar 233 GHz flux. This approach, illustrated in Fig. A1, yielded 1.26 Jy for J0519-4546 and 1.20 Jy for J2258-2758 on August 8, 2021. For the latter object, the value is also nicely consistent with the few available 233 GHz measurements. Moreover, J2258-2758 is also monitored at ∼225.5 GHz from the SMA. Interpolating between 225.5 GHz measurements from July 6, July 9 and August 17, 2021, and applying a spectral index of -0.68 (see Fig. A1) leads to a 233 GHz flux of 1.24 Jy, comparing well with the above 1.20 Jy value. We finally adopt a 1.22 Jy flux for J2258-2758, with an estimated 2% uncertainty.

As indicated in the main text, each of the two scheduling blocks used the same phase calibrator, J0253-5441. The latter is not monitored in terms of flux at ALMA. However, calibrating the visibilities on each flux/bandpass calibrator yielded two independent measurements of its flux, namely 0.374 and 0.389 Jy for the two SBs (Table I). We adopt the relative difference, 4%, as a conservative estimate on the absolute uncertainty. This uncertainty is dwarfed by the S/N-limited error bar on the 2014 UN271 flux, equivalent to 9%, but was taken into account in the final error bar.

Appendix B: Dust signal estimation

We estimated the coma flux density at 233 GHz in the ALMA 0.067” × 0.062” synthesized beam on the basis of reported optical aperture photometry. In practice we used the Afp value of ~150 m deduced from the observations of C/2014 UN271 on 29 June 2021 (r = 20.15 au) (Dekelver 2021) (see also Bernardinelli et al. 2021). The Afp parameter, where A and f are the grain albedo and the filling factor of the instrument of view with projected radius ρ, is independent of ρ if the line of sight column density falls off as 1/ρ, as expected for steady and isotropic dust production (A Hearn et al. 1984). Afp is proportional to the dust production rate, with a coefficient of proportionality that depends on the particle size and velocity distributions. Both the independence on ρ, and the increase of Afp as 2014 UN271 approached the Sun from 28 to 20 au, is consistent with Afp measuring the actual activity rate of the comet Bernardinelli et al. 2021).

Our estimation of the coma flux density at 233 GHz is based on two steps: 1) the determination of the dust production rate Qd from the measured Afp using the Mie scattering calculations of Fink & Rubin (2012); 2) the computation of the dust thermal emission using the model of Bockelée-Morvan et al. (2017), also using Mie theory. Calculations were made for size distributions given by n(a)da ∝ a − β, where a is the particle radius and β is the size index. We considered a minimum size of 0.01 µm, and maximum sizes a max of 10 µm and 1 cm.

Appendix B.1: Dust production rate

Fink & Rubin (2012) provide the Qd/Afp ratio (kg s−1 / m) for particle sizes in the range 0.01 µm – 1 cm and various size index values. Their calculations were made for a refractive index n = 2.00 + 0.10i, a phase angle φ = 40° and particle velocities following v(a) = 0.1423 a−0.5 m/s, a being the particle radius in m (v = 142.3 m/s for a = 1 µm). We rescaled Qd/Afp to a phase angle of 3°, assuming a phase function ratio ρ(φ = 3°)/ρ(φ = 40°) = 2.42. This value matches the composite phase function of D. Schleicher (and is in the range of the values obtained from Mie calculations (Fink & Rubin 2012)). We also rescaled Qd/Afp to a velocity distribution v(a) = 0.083 a−0.5 m/s. Indeed, based on Ciofi & Rodionov (1997), we derived v = 83 m/s for a = 1 µm for 2014 UN271, using a nucleus radius of 68 km, nucleus and dust densities of 500 kg m−3 and 1000 kg m−3, respectively, and a CO production rate of 4 × 1028 mol s−1 emitted in cone of 45° half-aperture. The assumed CO production rate (1860 kg s−1) is reasonable but somewhat arbitrary. An upper limit of 2 × 1028 mol s−1 was derived from 4.6 µm NEOWISE observations at r = 20.92 au (Farnham et al. 2021). Moreover, extrapolating the CO production rate of ~4 × 1028 mol s−1 of comet C/1995 O1 (Hale-Bopp) measured at r = 14 au (Biver et al. 2002) (assuming a r−2 dependence) and correcting for the different nucleus sizes (37

http://smal.sma.hawaii.edu/callist/callist.html
km radius for Hale-Bopp, Szabó et al. (2012), yields an expected CO production rate of \(4 \times 10^{28}\) mol s\(^{-1}\). Using the nominal CO production rate of \(4 \times 10^{28}\) mol s\(^{-1}\), we estimated a maximum liftable size of \(8 \mu m\) following Zakharov et al. (2018). For a CO production rate of \(7 \times 10^{27}\) mol s\(^{-1}\), the maximum liftable size is only 1.3 \(\mu m\). Calculations for \(a_{\text{max}} = 1.3 \mu m\) were not performed, but that case would obviously lead to even smaller dust production rates and thermal flux densities than those reported in Table B.1 for \(a_{\text{max}} = 10 \mu m\).

### Table B.1: C/2014 UN\(_{271}\) dust mass loss rate and flux density in ALMA beam.

| Size index | \(a_{\text{max}}\) (µm) | \(Q_{d}/A_f \rho^a\) (kg/s/m) | \(Q_d\) (UN\(_{271}\))\(^b\) (kg/s) | \(F(233\) GHz)\(^c\) (mJy) |
|------------|-----------------|-------------------------------|---------------------------------|-------------------------------|
| 3          | 10 µm           | 0.291                         | 43.6                            | 9.9 \(10^{-6}\)              |
|            | 1 cm            | 56.9                          | 8544                            | 1.5 \(10^{-2}\)              |
| 3.5        | 10 µm           | 0.338                         | 50.7                            | 1.0 \(10^{-5}\)              |
|            | 1 cm            | 9.16                          | 1374                            | 2.8 \(10^{-3}\)              |
| 4          | 10 µm           | 0.425                         | 63.7                            | 1.1 \(10^{-5}\)              |
|            | 1 cm            | 0.488                         | 73.2                            | 8.6 \(10^{-5}\)              |

\(a\) Rescaled from values of Fink & Rubin (2012), see text.

\(b\) For \(A_f = 150\) m (Dekelver 2021).

\(c\) In a 0.064” beam width at \(r_b = 20.0\) ua and \(\Delta = 19.68\) ua.

### Appendix B.2: Thermal flux of the dust

To compute the expected dust emission at mm-wavelengths, we then used the model described in Bockelée-Morvan et al. (2010), here with the assumption of a Gaussian beam. This model has also been used to analyse ALMA/ACA observations of C/2015 ER61 (PanSTARRS) and mid-infrared data of comet 29P/Schwassmann-Wachmann (Roth et al. 2021). Schambeau et al. (2021). The dust local density is described as in Fink & Rubin (2012), i.e., follows a 1/\(r^2\) \(v(r)\) law, where \(r\) is the distance to nucleus. The flux density is computed by summing the blackbody thermal emission of individual particles over the size range, and field of view, weighted by the particle size distribution. For consistency with the model of Fink & Rubin (2012), the dust density was taken equal to 1000 kg m\(^{-3}\). The computed flux densities in a Gaussian beam of half-power beam width HPBW = 0.064” (corresponding to the ALMA synthesized beam) are given in the last column Table B.1 and shown in Fig. B.1. We note that the derived flux values are not dependent on the adopted scaling constant in the dust velocity law, since the same velocity law is used for the \(Q_d/A_f \rho\) and flux calculations.

### Appendix B.3: Visibility curve for dust thermal emission

For comparison with the measured visibility curve (Fig. 2), we also calculated the dust signal in terms of the visibility flux at 220 kÅ. In their Appendix A, Bockelée-Morvan et al. (2010) provide formulas describing how the amplitude of the visibility \(V\) varies as a function of UV radius \(\sigma\), for a brightness distribution varying as \(1/\sigma^2\). This includes the formula for the visibility at \(\sigma = 0\) m, corresponding to the signal in the primary beam. The formulas are given for molecular lines, but can be applied to the dust coma, adjusting the factors describing the emission mechanism. From Eq. A.3 and A.4 of Bockelée-Morvan et al. (2010),

\[
V(\sigma) = \frac{K}{\sigma^2} \quad \text{(B.1)}
\]

for \(\sigma / D_{\text{beam}} \gg 0.2\), where \(D_{\text{beam}}\) is the HPBW of the primary beam, and

\[
V(0) = K \sqrt{\frac{\pi}{4\ln(2)}} \Pi_{\text{beam}} \quad \text{(B.2)}
\]

where \(\Pi_{\text{beam}}\) is the HPBW of the primary beam, this time in radians. \(K\) is a constant that incorporates factors related to the emission mechanism and the distance of the comet to the observer. Equation B.2 is derived from Eq. A.4 of Bockelée-Morvan et al. (2010), here with the assumption of a Gaussian beam. Equation B.2 can also be used for the signal in the synthesized interferometric beam \(F_{\text{synth}}\), replacing \(\Pi_{\text{beam}}\) by the angular size of synthesized beam \(\Phi_{\text{synth}}\). Hence,

\[
V(\sigma) = \frac{c}{\sigma^2} \sqrt{\frac{4\ln(2)}{\pi}} \frac{1}{\Pi_{\text{synth}}} = \lambda \sqrt{\frac{4\ln(2)}{\pi}} \frac{1}{\Pi_{\text{synth}}}, \quad \text{(B.3)}
\]

From this formula, the visibility flux at 220 kÅ from the dust coma is 4.40 times the flux in a 0.064” beam.

Based on Table B.1 and Fig. B.1 it appears that in virtually all cases is the expected thermal emission of dust entirely negligible. Only in one case (size index \(\beta = 3\), \(a_{\text{max}} = 1\) cm), does

\[\text{(B.1)}\]

For a uniform circular aperture with same HPBW, the \(\sqrt{\text{area}} = 1.064\) term would be replaced by 1.
the dust contribution amount to \( \sim 12\% \) of the measured signal in the interferometric beam. Another way of seeing it is that this extreme case corresponds to a visibility of \( 0.015 \times 4.4 = 0.066 \) mJy at 220 k\( \lambda \), well within the 3-\( \sigma \) measured upper limit of 0.1 mJy. The latter value corresponds to an upper limit of the dust contribution to the synthesized beam flux of \( 0.1 / 4.4 = 0.023 \) mJy, which is plotted in Fig. B.1. We note finally that although Farnham et al. (2021) argued that the coma of 2014 UN\( \text{271} \) consists mostly of submillimeter sized particles emitted at low velocities, this does not appear consistent with our above estimate of the maximum liftable size. Even if this was the case, the contribution of the coma to the thermal flux would be negligible, based on interpolation between the \( d_{\text{max}} = 1 \) cm and \( d_{\text{max}} = 10 \) \( \mu \)m cases in Table B.1 and Fig. B.1.

\( ^{12} \) and even less considering possible flux losses due to missing short spacing.