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A Study on the Great Comet of 2024: C/2023 A3 (Tsuchinshan-Atlas) via Radio Interferometry

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ABSTRACT

Our solar system is approximately 4.5 billion years old. Comets are remnants of its formation, serving as time capsules to give us an understanding of its natal heritage. Revealing our own solar system's history allows us to gain insights into other young stellar systems and the potential for life elsewhere. C/2023 A3 (Tsuchinshan–ATLAS) was a comet from the Oort cloud on its first and possibly only journey to the inner solar system. The comet grew in brightness to a visual magnitude of -4.9 on October 9, 2024, making it temporarily brighter than Venus and one of the brightest comets of the past century. Spectroscopic observations of comet A3 were conducted on October 1, 2024, using the Atacama Large Millimeter Array (ALMA) radio telescope located in the Atacama Desert in Chile. The Band 8 receiver centered near 460 GHz was used to sample thermal continuum emission from the nucleus and dust in the coma, as well as spectral line emission from CH_3OH (methanol), SO (sulfur monoxide), and NH_2D (ammonia). Continuum emissions were detected, but spectral line emissions were not detected. Continuum properties of the dust coma were modeled following the methods of (E. Lellouch et al. 2022). Calculated dust mass and upper limits on the size of the nucleus will be discussed. Future work will entail comparing upper limits on molecular abundances in A3 against other compositional studies that determined it to be depleted in carbon-chain molecules.

1. INTRODUCTION

Comets are important to understanding the formation of the early solar system. They are time capsules containing ices of various chemicals from simple molecules like H2O and CO, to more complex molecules such as methanol and formaldehyde (Caroll p. 870). And the comets which have been preserved the best are the comets which were cast out into the Oort cloud by interactions with the heavier gas and ice giants (Caroll p. 873). At a distance ranging from 3000 AU to 20,000 AU for the inner Oort cloud and 20,000 AU to 100,000 AU for the outer Oort cloud, these comets preserving unaltered materials from the era when our solar system first emerged from a protoplanetary disk (Carroll p. 873). Comet C/2023 A3 (Tsuchinshan-Atlas) (hereafter referred to as A3) is one such comet.

Comet C/2023 A3 (Tsuchinshan-Atlas), discovered independently by the Tsuchinshan Observatory and the ATLAS survey, has attracted considerable interest due to its anticipated brightness and favorable observing conditions during its closest approach to Earth (Tang 2024). Projected to reach a perihelion of 0.391 AU, this comet offers a rare opportunity to study an Oort cloud comet in unprecedented detail (Tang 2024). Based on current calculations[4], comet A3 has been ejected from our solar system and will never be seen again. Collecting as many observations as possible with multiple modalities is critical due to the unpredictability and transient nature of Oort cloud comets.

This study presents observational analyses of the recently discovered comet C/2023 A3 (Tsuchinshan-Atlas), employing high-resolution radio interferometry data from the Atacama Large Millimeter/submillimeter Array (ALMA), including observations from both its 12-meter main array and the Atacama Compact Array (ACA). ALMA's un-

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[4] Eccentricity >1 based on ephemeris from JPL Horizons current as of May 7, 2025.

paralleled sensitivity and spatial resolution at millimeter and submillimeter wavelengths make it uniquely suited to investigate the composition and structure of cometary nuclei and their surrounding comae.

Furthermore, through observations of comet A3, we aim to characterize upper limits for molecular abundances, dust mass, grain size, and nucleus diameter, thus providing direct constraints on the comet's chemical and physical properties. These data are crucial for enhancing our understanding of cometary activity, refining models of comet formation and evolution, and offering a broader perspective on the diversity and origins of primitive material within the solar system. Ultimately, insights gained from C/2023 A3 will contribute significantly to our knowledge of the pristine conditions prevalent in the outermost reaches of our planetary system now and in the distant past.

2. OBSERVATIONS AND DATA REDUCTION

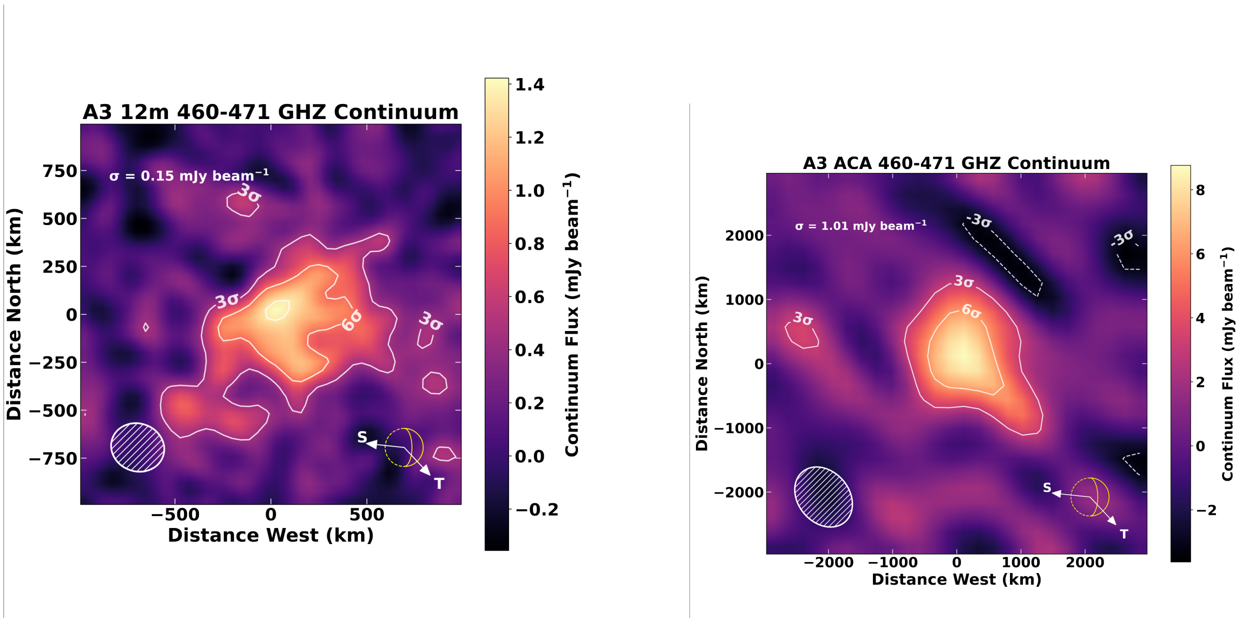
Observations were collected on UT 2025 October 1 between 14:31 and 16:10 UTC on A3 and three calibration targets, quasars J1058+0133, J1118-1232 and J1130-1449. The precitable water vapor was 0.76 - 0.84 mm. Data was collected using ALMA Band 8 over four spectral windows centered at 459.127 GHZ, 461.079 GHZ, 470.383 GHZ, and 472.127 GHZ with 128, 960, 960, and 3840 channels and 15,625 kHz, 244.141 kHz, 244.141 kHz, and 488.281 kHz channel widths respectively for a total of 2 GHZ, 234.375 MHz, 234.375 MHz, and 1.875 GHz total bandwidth respectively. The 12-meter configuration utilized 47 antennas while the ACA configuration utilized 14 antennas. This yielded, for the 12-meter configuration, baselines from ˜25 - 400 meters. Comet A3 was at a heliocentric distance of approximately 0.406 au moving away from the Sun at an apparent speed of roughly 12.4 km/s. It was at a geocentric distance of approximately 0.74 au moving at 71 $\mathrm{km\,s^{-1}}$ towards the telescope.

The data was delivered as two measurement sets processed through the CASA Pipeline. To begin, the measurements sets were split to separate the quasar calibrators from the comet. Then those filtered measurement sets were processed using the ***tclean*** task in CASA (J. P. McMullin et al. 2007). Spectral windows 0 and 3 were chosen to analyze the continuum due to their high channel count and broad bandwidth. Once images were generated, they were cleaned by removing the background noise. Images of continuum for the 12m and ACA were opened using the CASA ***imview*** command. The comet, which was detected near the bottom, right edge of the image, was demarcated by an elliptical region by hand. Then the rms value of the region of the image not contained in the comet region was measured and subtracted from the background to generate a clean continuum image. For improved visualization, the comet was centered using the ***fixplanet*** and ***phaseshift*** CASA commands.

Figure 1 shows the continuum from 460 to 471 GHz for the 12m and ACA arrays. The comet is centered at position 0, 0 and the x and y axes indicate distance from the comet centroid determined by the comet region discussed previously. The x axis indicates distance west of the centroid as positive values and distance east as negative values. Likewise, the y axis indicates distance north of the centroid as positive values and distance south as negative values. The color indicates the average continuum flux per beam in units of mJy. Contours indicate multiples of 3σ confidence levels. The synthesized beam is shown in the lower, left. The orientation of the comet is indicated in the lower, right. S denotes the direction towards the sun. T denotes the direction of the comet's tail. The sphere indicates how the comet is being illuminated by the sun.

Figure 2 shows the results of the channel averaging and binning with a width of 24 meters. Each individual point is the real part of the complex visibility where the error bar is calculated according to the propagation of errors described in section 4.1 ofC. A. Nixon et al. (2020). The fitted lines represent model assuming a constant flux for the nucleus (point) and $1/\rho$ flux for the coma. Least squares fitting was performed using the **lmfit** Python package. The red line was fit assuming zero flux contribution from the coma. The green line was fit assuming zero flux contribution from the nucleus. The blue line was fit assuming non-zero flux contributions from the nucleus and coma. The x axis is baseline distance in meters, and the y axis is flux density measured in janskys.

To facilitate further calculations, the visibilities of the two spectral windows at 459 GHz and 472 GHz were combined. Since visibilities from different frequencies were averaged together, the spectral behavior of continuum emission had to be considered. Since the intensity of blackbody radiation for an object of a given temperature varies with frequency, simply averaging together fluxes would not give a representative measure of the object's thermal emission. Fluxes from different frequencies were converted to a common scale using the spectral index, which assumes that flux as a function of frequency follows a power law: $F_1/F_2 = (\upsilon_1/\upsilon_2)^x$, where x is the spectral index, and $F_i$are the fluxes at each frequency υ (Roth, 2025). The first spectral window centered on 459 GHz was chosen as the common frequency and 1.93 given by Lelouch et al. (2022) was used as the spectral index.



(A) (B)

Figure 1. **(A).** Continuum from 460 to 471 GHz for the 12m array. The comet is centered at position 0, 0 and the x and y axes indicate distance from the comet centroid determined by the comet region discussed previously. The x axis indicates distance west of the centroid as positive values and distance east as negative values. Likewise, the y axis indicates distance north of the centroid as positive values and distance south as negative values. The color indicates the average continuum flux per beam in units of mJy. Contours indicate multiples of 3σ confidence levels. The synthesized beam is shown in the lower, left. The orientation of the comet is indicated in the lower, right. S denotes the direction towards the sun. T denotes the direction of the comet's tail. The sphere indicates how the comet is being illuminated by the sun. **(B).** Continuum for the ACA array. JJB: Figures aren't aligning properly and I'm not sure what the black lines are adjacent to the y axis.

3. RESULTS

To calculate nucleus size, the individual baseline visibilities were averaged over channel and binned. Then the binned visibilities were fit using least squares with the **lmfit** Python package. The measured flux was assumed to be constant at the nucleus and follow a $1/\rho$ curve for the coma, where ρ is the distance from the nucleus (Roth, 2025). JJB: Results from dust_model_lmfit function go here. Finally, using a 3σ upper bound for the intercept parameter, equation 19 from Delbo & Harris (2002) based on the NEATM model was rearranged to solve for nucleus diameter, giving an upper limit of 10.2 km.

To calculate dust mass, we chose the flux value at the shortest (binned) baseline. The overall integrated dust continuum flux is best determined by the shortest baselines, which sample the widest angular scales (Roth, 2025). We rearranged Equation 5 from Roth et al. (2023) to solve for dust mass, M. The temperature for the dust grains was calculated using a simple equilibrium law, $T\,(r_H) = (277\ K)(1 - A)/\sqrt{r_H}$, where r_H is the heliocentric distance measured in AU, and A is the Bond albedo. The Bond albedo was assumed to 0.0212. Dust opacity numbers were assumed to be astronomical silicates and gathered from Table 5 by Boissier et al. (2012). A range of dust opacities was obtained assuming a size index of -3, a grain size range of $10^{-4} - 10$ mm, porosity of 50%, wavelengths of 0.8 and 0.45 mm (459 GHz is ˜0.65 mm), and ice fractions of 0%, 22%, and 48%. Finally, 3σ upper limits of dust mass were calculated to be $5.2 - 8.4 \times 10^7$kg assuming a flux of 6.037×10^{-3} Jy and $\sigma = 2.152 \times 10^{-3}$.

4. DISCUSSION

An upper bound nucleus size of approximately 10.2 km for comet C/2023 A3 (Tsuchinshan-Atlas) places it within typical ranges observed for long-period comets according to Meech et al. (2004) albeit a bit on the low end of the spectrum. According to their analysis of long-period comets, comet nuclei ranged from <4 to 56 km in size. Comet Hale-Bopp, a notably large comet long-period Oort cloud comet, had a nucleus diameter around 40–60 km. What is notably anomalous is the range of calculated dust masses. Our value of $5.2 - 8.4 \times 10^7$ seems too high by one or two

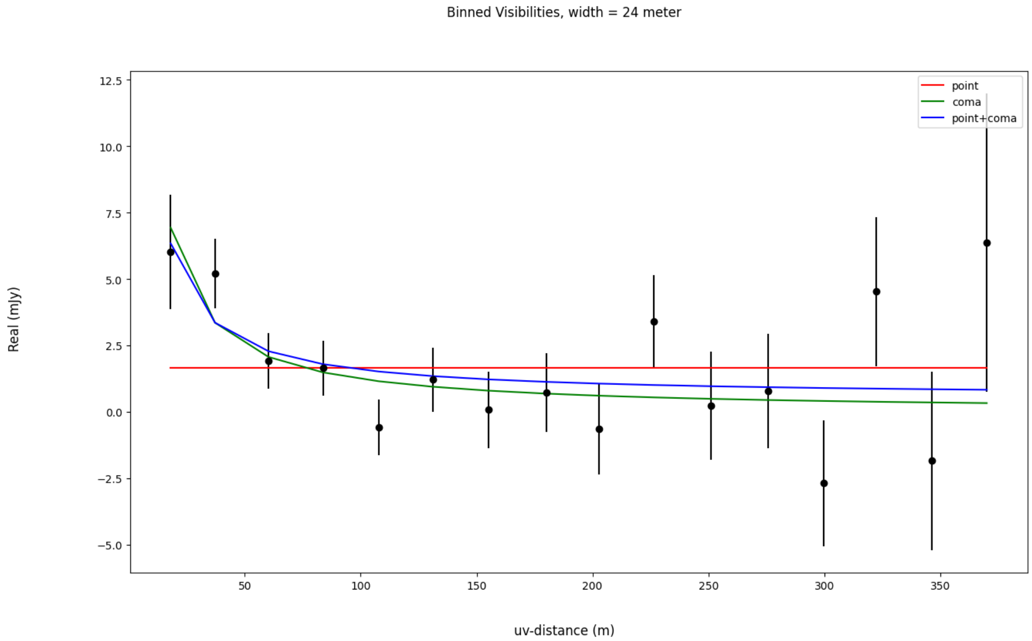


Figure 2. Results of the channel averaging and binning with a width of 24 meters. Each individual point is the real part of the complex visibility where the error bar is calculated according to the propagation of errors described in section 4.1 ofC. A. Nixon et al. (2020). The fitted lines represent model assuming a constant flux for the nucleus (point) and $1/\rho$ flux for the coma. Least squares fitting was performed using the **lmfit** Python package. The red line was fit assuming zero flux contribution from the coma. The green line was fit assuming zero flux contribution from the nucleus. The blue line was fit assuming non-zero flux contributions from the nucleus and coma. The x axis is baseline distance in meters, and the y axis is flux density measured in janskys. JJB: The text is too small. Legend should have $\chi^2_{residual}$ values from lmfit. Should this instead be in results?

orders of magnitude based on dust production observations and simulations done by Moreno et al. (2025). However, this range of masses is still below measurements of large comet dust masses such as comet Hale-Bopp, which had an estimated dust mass of $4.7 \pm 1.1 - 5.3 \pm 1.2 \times 10^{11}$ kg when it was within 1 AU according to Jewitt & Matthews (1999). One likely source of error is an improper dust opacity. Future work will be needed to determine appropriate estimates for grain size, ice content, etc. to find or model more appropriate dust opacities.

We did not detect any molecular spectral lines for methanol or sulfur monoxide. Both Tang et al. (2024) and Cambianica et al. (2025) measured a depleted comet. Cambianica et al. (2025) were able to detect CN molecular lines in the visual spectrum using the DOLORES spectrograph and derive a production rate, but they detected no other species. They also measured a large dust opacity, in line with observations by Tang et al. (2024), and also in line with our calculations of a rather massive dust coma, which may serve to obscure any molecular lines in the visible spectrum. Also, our detection of the comet continuum was only to ˜6σ confidence compared to $>10\sigma$ for Lelouch et al. (2022). Nevertheless, we intend to calculate upper limits for CH_3OH and SO production rates using the SUBLIMED model (Cordiner 2022). Since we lacked detection of these lines, we can calculate an upper limit for production rates. If production rates exceed had exceed these modeled upper limits, then we should have detected them.

5. ACKNOWLEDGEMENTS

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