

Preserved primordial material detected in a Centaur coma 9 au from the Sun

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Article

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Posted Date: June 1st, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-9857535/v1>

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Additional Declarations: There is **NO** Competing Interest.

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Abstract

The frigid interiors of Trans-Neptunian objects (TNOs) and Centaurs, the dynamical descendants of TNOs scattered inward of Neptune’s orbit, preserve pristine material that have been shielded from cosmic rays and insolation since the planetary formation era. A small fraction of Centaurs provides means to study these otherwise inaccessible interiors during activity outbursts that expel subsurface material into a coma. Here we present observations of an outburst from the Centaur C/2023 RS61 (PANSTARRS) from the James Webb Space Telescope, Hubble Space Telescope, and Gemini North Telescope. We show that its unusual ultra-red coma dust grains are rich in organic and nitrogen-bearing compounds and have a reflectance spectrum remarkably similar to the surfaces of primitive Cold Classical TNOs, suggesting C/2023 RS61 (PANSTARRS) formed at the outermost edge of the protoplanetary disk. Our results further indicate that such pristine material can be preserved in objects later scattered into the giant-planet region. We found that the coma dust grains were excavated from a ~ 30 m deep cavity, offering a first glimpse of preserved interior material from a small Cold Classical TNO. Finally, we conclude that the bulk composition of small Cold Classical TNOs is mostly homogeneous, based on the spectral similarity between the excavated dust grains and the surfaces of Cold Classical TNOs.

Keywords: Centaur group (215); Comets (280); Infrared spectroscopy (2285); James Webb Space Telescope (2291); Broadband Photometry (184); Hubble Space Telescope (761); Ice spectroscopy (2250); Carbon dioxide (196); Complex organic molecules (2256); Molecular spectroscopy (2095); Coma dust (2159);

Trans-Neptunian objects (TNOs) contain some of the most primitive material remaining from the formation of the Solar System, offering a glimpse into the physicochemical conditions present during the planetesimal accretion phase [1–3]. The near-infrared reflectance spectra collected with the James Webb Space Telescope (JWST) [4] have

revealed three major compositional surface groups classified by [5] as H₂O-type, CO₂-type, and organics-type [4]). Each group exhibits distinct spectral signatures from simple ices, complex organics and mineralogical components that provide hints into the their formation conditions.

However, a variety of acting surface-altering processes such as cosmic ray irradiation and volatile sublimation complicate the interpretation of present-day TNO surface compositions as direct tracers of their primordial material inventories [6]. One way to access the shielded TNO interiors, containing preserved primordial materials, is through observations of their dynamical descendants, the Centaurs, which have been scattered from their original locations through gravitational interactions with Neptune into the giant planet region. Centaurs eventually dynamically evolve inward to become Jupiter-family comets (JFCs) [7] on ~ 10 Myr timescales. Notably, approximately 10% of the known Centaur population exhibits cometary activity [8–11] even before becoming JFCs. A rare type of centaur activity called outbursts can expel material from relatively deep nuclear regions into comae [12–17], providing a valuable opportunity to probe the interior materials of former TNOs.

Here we present results from a multi-wavelength observational study of active Centaur C/2023 RS₆₁ (PANSTARRS), hereafter RS61, following its last outburst that occurred between UTC 2025 August 8–10 [18]. RS61 is one of only four Centaurs known to exhibit recurrent outburst activity; the others are 29P/Schwassmann-Wachmann 1 [19–23], 174P/Echeclus [24–26], and 95P/Chiron [27–30]. RS61’s has a relatively small nucleus, $4.7 \text{ km} \leq r_n \leq 7.0 \text{ km}$ [31], closer in size to a typical JFC [32, 33]. The other three are comparably larger, with 29P and 174P both around $r_n \sim 30 \text{ km}$ [24, 34–36] and Chiron at $r_n \sim 100 \text{ km}$ [37]. So, RS61 provides an opportunity to probe behaviors in Centaurs at the small end of the know nuclei size distribution [38, 39].

Numerical orbital integrations reveal RS61 is a dynamically new Centaur that left the TNO regions $\sim 0.5\text{--}1$ Myr ago (Fig. 6b) that still possesses a relatively high perihelion distance (8 au).

Our broadband optical observations acquired with the Gemini North telescope after outbursts in 2025 January and another in 2025 August (see Methods) revealed that RS61 has the reddest photometric color ever detected among active Centaurs and comets, at $g'-r' = 0.85 \pm 0.02$ ([18, 40]), a color similar to the red surfaces of the most primitive Cold Classical TNOs [41]. For comparison, the outburst dust comae of 29P, 174P, and Chiron are all blue to neutral [8, 42, 43], typical of small grains with an abundant ice content [44], while red dust comae are typical of large, organic-rich and ice-poor dust grains [45, 46].

Because of RS61’s one-of-a-kind red coma, we acquired Near-infrared (NIR) spectra using the JWST NIRSpec instrument approximately 36 days after the UTC 2025 August 8–10 outburst to investigate the composition of the ultra-red dust grains. The spectrum was acquired while RS61 was at ($R_H \sim 9$ au) and shows scattered sunlight from the outburst dust coma, with a negligible contribution from RS61’s nucleus. The measure flux near RS61’s nucleus’s location is ~ 3 orders of magnitude higher than what is expected from its small nucleus alone. Additionally, spectra extracted across the NIRSpec integral field unit (IFU) field of view (FOV) away from

any nucleus contribution are nearly identical except for subtle variations of absorption feature band depths, providing further confidence that the measured spectrum is dominated by the coma.

The overall shape of RS61’s relative reflectance coma spectrum, including the positions and depths of the absorption features (see Fig. 1a), is consistent with the most primitive organics-type TNO surfaces [5, 47] and also the Cold Classical TNO Arrokoth observed by the New Horizons spacecraft [48]. RS61 marks the first detection of this spectral type within the coma of an active object. Interestingly, no coma gas emission features were detected across the FOV.

As shown on Figure 1b, we have identified absorption features attributed to combination and overtone modes of O–H, C–H, and N–H groups at 1.5 μm , several bands of methanol (CH_3OH) at 2.27, 2.34, 2.5, and 3.9 μm , carbon dioxide (CO_2) $\nu_1 + \nu_3$ combination band at 2.7 μm and ν_3 asymmetric stretching fundamental at 4.27 μm , O–H and complex organic molecules, including aliphatic C–H stretching modes between 3.33–3.6 μm , $\text{C}\equiv\text{N}$ -bearing organics between ~ 4.3 –4.5 μm , OCN^- at 4.62 μm , and a feature around 4.9 μm possibly from OCS or methanol. The O–H contributions near 3 μm may partially be attributed to water ice, but the absorption features are likely dominated by methanol and complex organics.

Our data show that RS61 is among the few organics-type Centaurs observed with JWST [49], where the majority of available JWST Centaur spectra belong to ‘ H_2O -types’ with a strong presence of water-ice, or have ‘shallow-bowl’ spectra interpreted as the presence of devolatilized silicate-rich mantle [50–52].

More precisely, RS61’s spectrum is similar to the weak methanol organics-type TNO subclass associated with the surfaces of Cold Classical TNOs [52]. This is confirmed through a Principal Component Analysis (PCA) of the band areas calculated following the methods of [4, 51, 52], and is shown in Fig. 2. The unique nitrogen-bearing features near 4.5 μm have only been detected on the surface of one other Centaur 2002 KY₁₄ [51, 52]. The presence of OCN^- (cyanate ion) at 4.62 μm , a common product of energetic processing of interstellar ices [53], also indicates a presence of preserved interstellar ice material embedded in the grains. The detection of such material in RS61’s coma and on the surface of 2002 KY₁₄ could mean that Centaurs are in fact a missing link capable of transporting nitrogen-bearing material from the outer transneptunian region to the inner Solar System [51], and that there might be a higher abundance of pristine material from the epoch of planetesimal formation in the inner Solar System than previously thought [51, 52].

There are some important nuances in the CO_2 and methanol abundances in RS61’s coma spectrum when compared to the organics-type TNO surfaces (Fig. 3). The 2.7 μm CO_2 band area seen in RS61’s coma is typical of the Eccentric TNO subgroup, whose members are observed in the Scattered Disk [52]. However, both the CO_2 band at 4.27 μm , which is 3–4 times weaker than in organics-type TNOs, and a missing right wing on the 4.33 μm CO_2 fundamental band indicate that the CO_2 abundance in RS61’s coma grains is smaller, similar in behavior of an emerging trend of reduced CO_2 ice with decreasing perihelion among the TNO population [54]. The smaller CO_2 abundance in RS61’s coma is consistent with the material sourced from its interior because of suggestion that some CO_2 ice detected on TNO surfaces is a

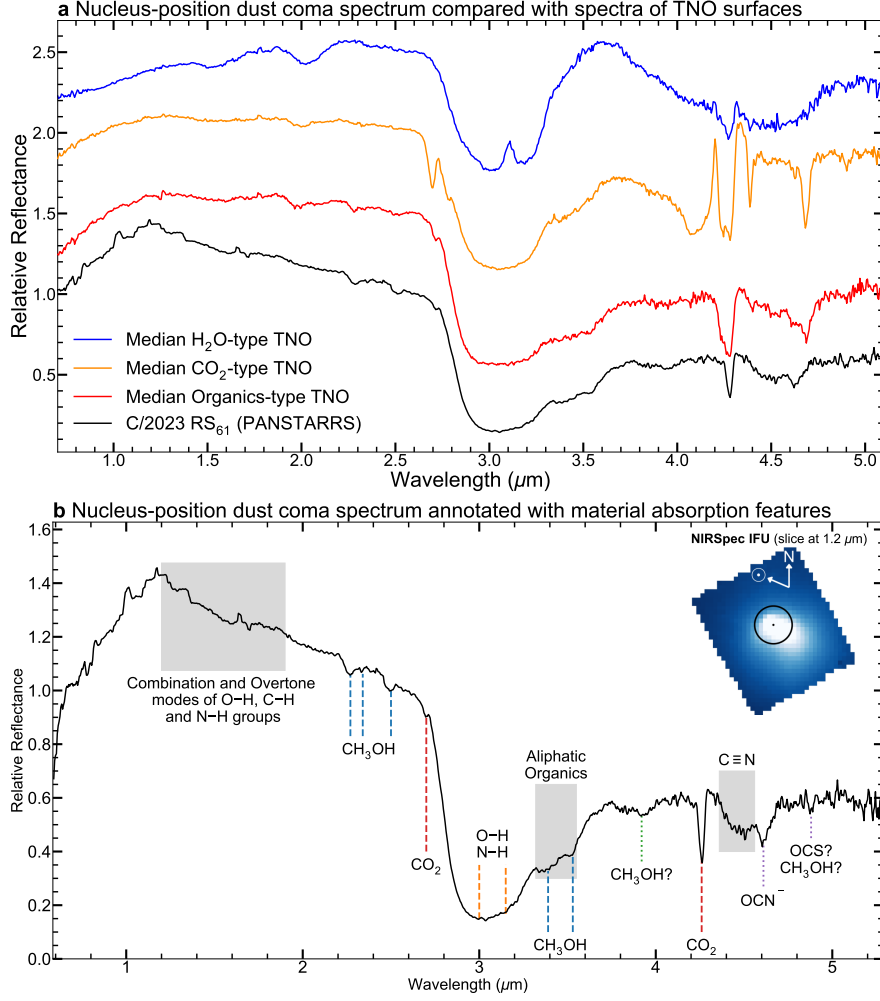


Fig. 1 Relative reflectance spectrum of Centaur RS61 obtained with JWST NIRSpect. (a) RS61’s spectrum (black) is compared to the three median TNO spectral types revealed by the DiSCo-TNOs survey [4] (H_2O -type, blue; CO_2 -type, orange; and Organics-type, red). RS61’s coma spectrum is most consistent with the surfaces of the organics-type TNOs. (b) Absorption features associated with CO_2 , methanol ice and other organic and nitrogen-bearing compounds are indicated in RS61’s spectrum by vertical dashed lines. The blue inset image shows the outburst coma in the NIRSpect integral field units (IFU) field of view (FOV) at 1.2 μm , where the black circle represents the 0.45'' radius photometric aperture used for extracting the spectrum. Celestial north is identified in the inset, along with the projected sunward direction; RS61’s projected motion is nearly aligned with this direction. Spectral extractions across the IFU FOV are nearly identical, providing evidence that the coma flux dominates the spectrum.

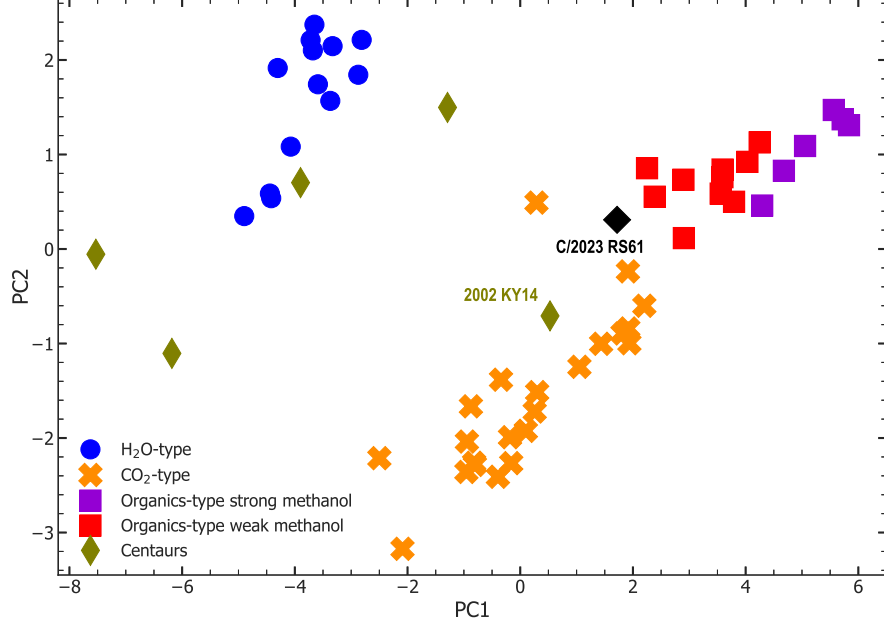


Fig. 2 Principal Component Analysis (PCA) of active Centaur RS61 (black diamond) projected into Principal Component 1 and 2 of TNOs and inactive Centaurs, including 2002 KY₁₄, observed by the DiSCo-TNOs JWST programme, with colors and symbols for TNOs corresponding to their spectral category. The PCA is restricted to the 1.7–4.6 μm range. This figure shows that the coma of active Centaur RS61 is more similar to the organics-type strong methanol (also known as Cliff1), and organics-type weak methanol (also known as Cliff2) TNOs instead of the H₂O-type (Bowl) or CO₂-type (Double-dip) TNOs. RS61 is also more similar to the inactive Centaur, 2002 KY₁₄, than the three other active Centaurs that more closely resemble H₂O-type TNOs.

byproduct of methanol irradiation [52, 55], which would not have occurred for RS61’s excavated material. Additionally, the methanol bands in RS61’s spectrum are generally deeper and more defined than on the typical weak methanol organics-type TNOs [52], pointing towards dust grain material with a higher abundance of less irradiated sub-surface methanol. The shape of the 3.9 μm methanol band is also consistent with its thermally unstable amorphous form, which would have crystallized if exposed to the warmer temperatures on the surface [56]. Amorphous methanol crystallizes on hour-long timescales at temperatures >100 K in laboratory conditions [57–60], but the timescales are likely much longer at lower temperatures. We interpret the deeper methanol absorption bands, the weaker CO₂ signatures, and the presence of the thermally unstable amorphous methanol as further evidence of the coma material being sources from RS61’s nucleus interior and that is represents more pristine material when compared to Cold Classical TNO surfaces.

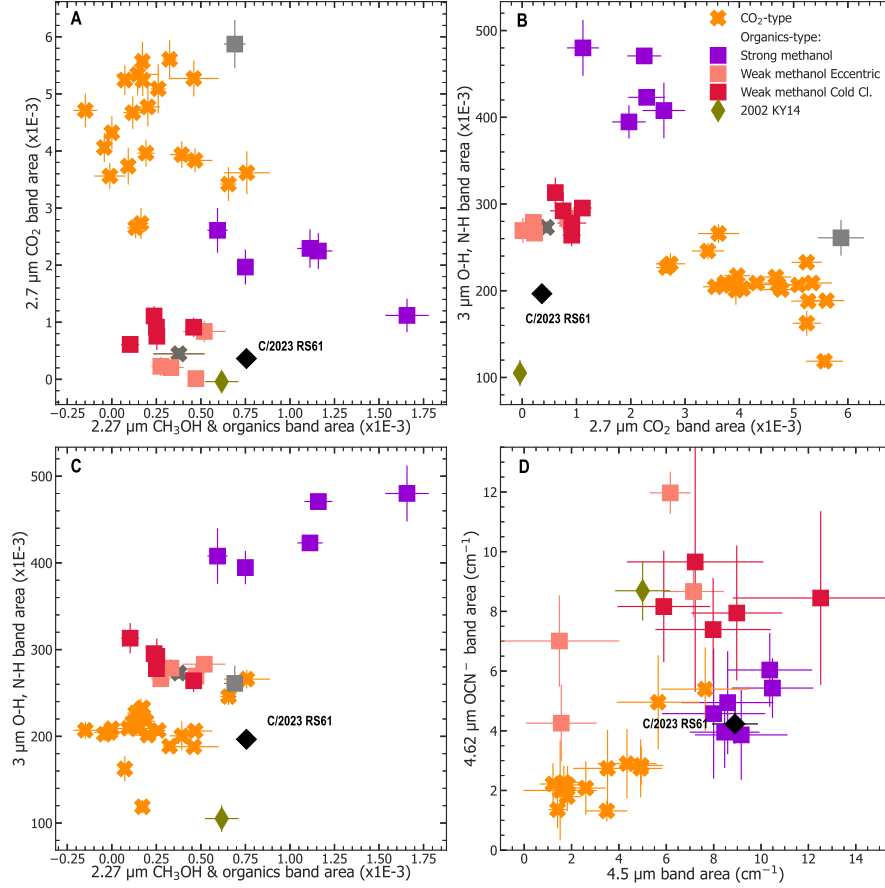


Fig. 3 Displayed are panels comparing the band areas of RS61 to those measured from spectra in the DiSCo-TNOs programme [4]. A: The 2.27 μm band area (CH₃OH and other organics) relative to the 2.7 μm CO₂ band area. B: The 2.7 μm CO₂ band area against the 3 μm band area, with contribution from O-H and N-H groups. C: The 2.27 μm band area compared to the 3 μm band area. D: The 4.5 versus the 4.62 μm band area, attributed to and to a CN triple bond and OCN⁻, respectively. In all panels, the grey symbols depict Huya and 2004 PG₁₁₅, two DiSCo TNOs that do not neatly fit into one of the spectral categories.

RS61's spectrum also has absorption features attributed to nitrogen-bearing species. A 4.62 μm OCN⁻ feature is clearly detected, but it is weaker than on weak methanol organics-type TNOs [51]. If the coma grains of RS61 are indeed less irradiated, it implies that OCN⁻ may either be an intrinsic property of the bulk composition or be produced with high efficiency from minimal CH₃OH irradiation in the presence of a stable N-bearing precursor [53]. A well defined absorption band at 4.5 μm can

179 be attributed to the CN triple bond, while methanol [57] is most likely not a major
180 contributor [51].

181 The turnover in the broad continuum shape near $1.2\ \mu\text{m}$ seen in RS61's coma
182 spectrum is similar to that observed in organics-type TNOs [47]. The steeper red slope
183 at wavelengths $<1.2\ \mu\text{m}$ is likely caused by a combination of absorption from tholin-
184 like macromolecular organics included in small grains and opaque minerals such as iron
185 sulfides, iron oxides, or metallic alloys [61, 62]. The steeper blue spectral slope longward
186 of $1.2\ \mu\text{m}$ is characteristic of scattering effects caused by a microporous texture of
187 refractory compound grains with sizes equivalent to or smaller than the wavelength of
188 scattered light. The combination of grain composition and size-dependent scattering
189 effects likely contribute to the observed shape of the $1.2\ \mu\text{m}$ peak [62, 63].

190 We further used broadband optical images acquired shortly before and after ($\pm$
191 1–3 days) the NIR spectrum to characterize the coma dust grains physical properties
192 and energetics of the outburst. The coma is elongated primarily in the anti-sunward
193 direction and has a nearly constant tail width, suggesting that grains were emitted over
194 a short interval with similar velocities and a sky-plane expansion speed of $\sim 2\ \text{m s}^{-1}$.
195 The lack of a detected coma extension in the sunward direction indicates that sustained
196 activity had ceased by the time of the observations. A surface-brightness profile along
197 the tail follows a power-law with slope ~ -1.1 to a distance of approximately $1''.75$,
198 corresponding to 10,750 km. The coma morphology and evolution, along with the
199 absence of gas emission, indicate that it was produced by a single, short-lived outburst
200 rather than by persistent activity.

201 We estimated a mass-weighted average dust grain radius of $10\pm 1\ \mu\text{m}$ and a total
202 mass of coma dust of $2.6\pm 0.9\times 10^7\ \text{kg}$ (see Methods) to better understand the nucleus
203 source of the outburst material. If this amount of dust was excavated from a cylindrical
204 pit with depth-to-width ratio of 0.75, as suggested for young Centaurs and new pits
205 [16, 64], and had a bulk density of $500\ \text{kg m}^{-3}$ [65] while incorporated in the nucleus,
206 the resulting pit would be approximately 45 m wide and 33 m deep (see Methods),
207 comparable to pits observed in situ on cometary nuclei [16, 64].

208 Overall, based on the similarity of RS61 coma material to the surfaces of Cold
209 Classical TNOs and the outburst coma's morphology consistent with a pit-forming
210 event, we suggest the bulk composition of RS61 is likely homogeneous; that is, the
211 surface is compositionally similar to the interior. We suggest this conclusion can also
212 be extended to the population of Cold Classical TNOs, given the similarities of their
213 surface spectra with RS61, and the low-temperature environments that they occupy.
214 These new finding place the TNO surface studies to date on a firmer footing as we
215 now know that the compositions measured can be interpreted as representing the bulk
216 materials present during their formation era.

217 As RS61 nears its perihelion on UTC 2028 December 10, the astronomical com-
218 munity is provided a rare opportunity to study the evolution of cometary activity of a
219 near-primordial small body only recently displaced from the trans-Neptunian region.

Methods

Discovery and Archival Observations

Centaur RS61 was discovered as a point source at a w-band ~ 21.9 mag by the Pan-STARRS survey on UTC 2023 September 15 when it was 10.1 au from the Sun [66, 67].

The first recognized evidence of cometary activity from RS61 came from imaging data obtained on UTC 2025 January 02 that revealed a faint (r'-band ~ 21.4 mag), broad fan-shaped coma almost perpendicular to the skyplane projected sunward and tailward directions at a heliocentric distance $R_H \sim 9.0$ au [31].

Later, [31] identified at least two additional, previously unnoticed episodes of activity in the Pan-STARRS1 survey archive [67] that occurred around UTC 2017 October 10 ($R_H \sim 13.5$ au) and 2023 September 25 ($R_H \sim 10.1$ au). Both episodes are consistent with outburst events due to the observed increases in brightness above the detection threshold, followed by subsequent fading to upper-limit non-detections consistent with pre-outburst levels. No discernible source extension from a coma or tail was detected in either event. However, the temporal sampling of the data was sparse, while the relatively large heliocentric distances and small solar phase angles of both events imply weak radiation-pressure effects made any source extension challenging to detect. Notably, the 2017 outburst at $R_H \sim 13.5$ au is the second-most distant outburst detected on a Centaur after 95P/(2060) Chiron, which holds the record at $R_H = 18.2$ au [29, 68]. RS61's last observed outburst occurred between UTC 2025 August 8-10 [18] and is the focus of this study.

Observations and Data Reduction

We obtained coordinated space- and ground-based observations of RS61 in 2025 September to characterize the aftermath of its 2025 August outburst. These observations included near-infrared spectroscopy with the JWST/NIRSpec, optical imaging with HST/WFC3, and supporting ground-based imaging from Gemini North. Together, these data show that the outburst produced a prominent, asymmetric coma extending in the anti-sunward direction, with unusually red organic and nitrogen-bearing materials present. The following subsections describe the observations and data reductions.

James Webb Space Telescope

Observations of RS61 were acquired on UTC 2025 September 11 between 07:48:43 – 11:12:18 with the JWST Near Infrared Spectrograph (NIRSpec) when the centaur was at $R_H = 8.93$ au, the JWST-RS61 distance was 8.52 au, and the solar phase angle was 6.11° . The observations were acquired through the Cycle 4 Director's Discretionary programme #9481 (Principal Investigator E. Lilly) and were scheduled through ultra-disruptive time to rapidly characterize the coma associated with the 2025 August outburst before it dissipated.

We obtained near-infrared integral-field unit spectroscopy using NIRSpec in IFU mode with the Prism/CLEAR setup. This configuration provides spectroscopy over

0.6–5.3 μm across a $3.0'' \times 3.0''$ FOV, corresponding to $18,573 \text{ km} \times 18,573 \text{ km}$ at RS61, with a spatial resolution of $0.1''$ and at a spectral resolving power $\lambda/\Delta\lambda = 30 - 300$ [69]. The observations were acquired using the NRSIRS2RAPID readout pattern and the standard four-point dither pattern, with offsets of approximately $0.4''$ between exposures, resulting in an effective on-target exposure time of 4726.8 s. The telescope tracked RS61 at its predicted non-sidereal rates provided by JPL Horizon.

Due to the extended nature of RS61, dedicated background fields were observed using the same configuration at an offset of $60''$ from RS61’s predicted ephemeris position at a position angle of $+90^\circ$ with respect to the Sun’s skyplane projected direction after the on-target observations in a non-interruptible sequence. The background fields were observed immediately after the science observations to ensure that the background obtained would be as accurately comparable to the target background as possible.

The raw uncalibrated data for each dither position and offset were downloaded from the MAST database using the `astroquery` Python package [70]. Each datacube was then processed with JWST pipeline version v1.19.2 [71]. The Calibration Reference Data System (CRDS) context file *jwst_1413.pmap*¹ was used for the data reductions.

A median-combined datacube was generated using the four individual datacubes from the on-target observations. The median-combined datacube was constructed by aligning the slices from the four individual datacubes in RS61’s non-sidereal frame and computing the median value at each spaxel (i.e., spatial pixel). A similar procedure was applied to the offset observations. Background subtraction was performed by subtracting the median-combined offset datacube from the on-target median-combined datacube on a slice-by-slice basis.

One-dimensional spectra covering the full wavelength range were extracted from the median-combined, background-subtracted datacube using aperture photometry with a circular aperture of radius $0.45''$. The skyplane projected radius of the circular aperture at the distance of RS61 was 2,781 km. The 1-sigma uncertainty was estimated using the local variability of the spectrum through a rolling standard deviation measurement using a window size of seven resolution elements. Figure 1 displays the spectrum extracted at the nucleus position after division by the spectrum of the solar analog star SNAP-2 [72] and normalized to one at $2.2 \mu\text{m}$. Spectral extractions across the IFU FOV are nearly identical.

The contribution of the nucleus to the near-nucleus spectrum depends on many factors, which include the shape and rotation state at the time of the observation, its albedo, color, and the thermal properties of the surface. [31] estimate an effective nucleus radius size between $4.7 \text{ km} \leq r_n \leq 7.0 \text{ km}$, assuming the end-member values for Centaur geometric albedos [$5\% \leq p_v \leq 11.2\%$; 73] and a spherical nucleus shape. A nucleus of this size would contribute a negligible signal to the spectrum. Because the spectral signatures remain consistent along the extended part of the coma away from the expected position of the nucleus, we conclude the observed spectral signatures reflect the composition of dust grains in the coma, and the contribution from the nucleus is negligible.

¹The CRDS context file used can be found at: <https://jwst-crds.stsci.edu/>.

304 Hubble Space Telescope

305 Observations of RS61 were acquired on UTC 2025 September 14 between 16:34:43 –
 306 17:07:02 with the HST Wide Field Camera 3 (WFC3) when the centaur was at
 307 $R_H = 8.93$ au, the HST-RS61 distance was 8.47 au, and the solar phase angle was
 308 5.92° . The observations were acquired through the Cycle 32 Director’s Discretionary
 309 programme #18196 (Principal Investigator E. Lilly) and were scheduled to accompany
 310 the JWST observation.

311 We obtained optical broadband imaging using the WFC3 UVIS instrument with
 312 the F350LP filter. The UVIS2-2K2C-SUB subarray was used, providing an approx-
 313 imately $81'' \times 81''$ FOV. Eight 60-s exposures were acquired using the four-point
 314 WFC3-UVIS-DITHER-BOX pattern, with $0''.173$ and $0''.112$ offsets arranged in a
 315 parallelogram to improve sub-pixel sampling, mitigate detector artifacts, and to help
 316 account for cosmic rays. A 0.2 s post-flash exposure was used to improve charge transfer
 317 efficiency during detector readout.

318 The charge-transfer-efficiency (CTE)-corrected flat-fielded calibrated `_flc.fits`
 319 images were downloaded from the MAST database using the `astroquery` Python
 320 package [70]. Cosmic ray artifacts were removed using the Python package `deepCR` [74]
 321 and by cross-comparing the individual exposures.

322 Figure 4 displays one of the HST images centered and cropped on RS61’s nucleus
 323 location. The outburst coma displays morphology consistent with a short-lived, impul-
 324 sive ejection event, with subsequent size-dependent separation of dust grains along the
 325 tail.

326 Gemini North

327 Ground-based observations of RS61 were acquired using the 8.1 m Gemini North
 328 telescope with the Gemini Multi-Object Spectrograph (GMOS) in imaging mode [75].
 329 The observations were scheduled to take place before the JWST observations in order
 330 to characterize and contextualize the wider coma morphology with to-be acquired
 331 spectra. Images were acquired using the equivalent SDSS g' , r' , and i' filters. A set
 332 of five 50 s exposures in (g' , r')-bands and 40 s exposures in i' -band were taken on
 333 UTC 2025 September 08, while a set of $4 \times r'$ and $3 \times g'$ images, each with 50 s
 334 exposure time were taken on UTC 2025 September 10. The short exposures were
 335 necessary to prevent the background from dominating due to the nearby full Moon
 336 that was separated from RS61 by 62° and 35° away, respectively, during the two
 337 nights. During the observations RS61 was at a heliocentric distance $R_H = 8.934$ au,
 338 geocentric distance $\Delta = 8.568$ au, and a phase angle $\alpha = 6.152^\circ$. The detector pixels
 339 with $0''.0807/\text{px}$ were not binned to take advantage of the excellent seeing, and a
 340 non-sidereal tracking was implemented to account for the target’s projected on-sky
 341 motion.

342 The GMOS images were reduced using our Python reduction pipeline including: (1)
 343 bias subtraction, (2) flat-field correction, (3) cosmic-ray removal performed utilizing
 344 the LACosmic technique [76] as implemented in `ccdproc` [77], (4) stacking of each
 345 filter’s individual images in the particular target’s non-sidereal and sidereal frames,
 346 and finally (5) a Pan-STARRS-based calibration using field stars from the central

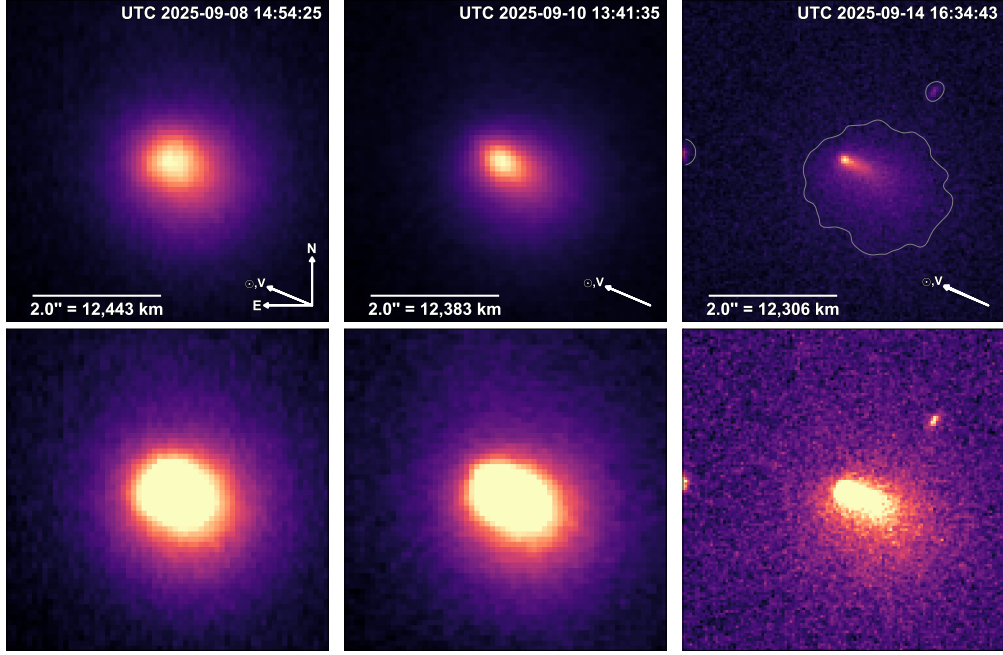


Fig. 4 Optical images of Centaur C/2023 RS61 (PANSTARRS) displaying the tail evolution. Data obtained from Gemini (left and middle panels) and HST (right panel) show the elongation of the tail due to solar radiation and subsequent grain size sorting. The top row displays the images using a logarithmic color scale to highlight near-nucleus surface-brightness morphology, while the bottom row displays the same image panels using a linear scale with a zscale contrast adjustment. Characterization of the outburst coma morphology evolution shows the coma is consistent with being sourced from a short-lived, impulsive ejection event, with subsequent size-dependent separation of dust grains along the tail.

GMOS CCD (which included the particular target) stacked in the sidereal frame. The Pan-STARRS (PS1) field stars' magnitudes are from the PS1 DR2 MeanObject tables reported in the AB magnitude system [78]. Corresponding AB magnitude photometry measurements, together with observing conditions, are included in Table 17.

Dust Grain Size Frequency and Ejecta Volume Estimates

The HST data were used to estimate the speed of the outburst ejecta dust, the dust's grain size-frequency distribution, the effective mass-weighted average size of the dust's grains, and the pit volume consistent with the amount of material detected.

The outburst coma evolution displays asymmetry dominated by elongation along the anti-sunward direction (i.e., along the dust tail; Fig. 4) suggestive of a grain size distribution under the influence of solar radiation pressure. The morphology seen

Table 1. Gemini North Observing Circumstances and Photometry

UT Date and time	Mean Airmass	Seeing ^a	Φ^b	SNR ^c	Filter ^d	m^e
2025/09/08 14:54	1.06	0.78	1.5	764.45	r'	18.53 $\pm$ 0.01
2025/09/08 15:06	1.07	0.78	1.5	253.93	g'	19.30 $\pm$ 0.01
2025/09/08 15:23	1.08	0.78	1.5	353.53	i'	18.13 $\pm$ 0.01
2025/09/10 13:42	1.06	0.47	1.5	506.29	r'	18.61 $\pm$ 0.01
2025/09/10 13:50	1.06	0.43	1.5	205.23	g'	19.39 $\pm$ 0.01

in the HST data constrains the skyplane-linear extent of the dust grains along and perpendicular to the tail direction.

The transverse width of the dust coma perpendicular to the tail direction is nearly constant in the HST data (see Fig. 5a). This semi-constant width suggests that grains of different sizes were emitted at similar speeds across a similar opening angle. The measured width was used to estimate an upper-limit to the skyplane expansion speed of $\sim 2 \text{ m s}^{-1}$, considering the outburst occurred ~ 36 day before the observations [18].

The skyplane-projected speed measured is reflective of the magnitude of the emission velocity in the sunward hemisphere. If material at RS61 were emitted at higher speeds in this direction, a measurable sunward extension would be detected due to grains prior to their turnaround due to radiation pressure. For example, grains with an assumed $\beta \approx 1$ have an expected turnaround distance at the observed geometry of $\sim 1''$ [79], increasing for lower β values. Such a sunward extension is not observed. Instead, the dust brightness is peaked near the nucleus's location, and the majority of the dust is extended along the tail direction.

A normalized radial surface-brightness profile along the tail is shown in Fig. 5b. The profile displays a power-law decrease in brightness from the nucleus's location to a distance of $\sim 1''.75$ (a skyplane distance of 10,750 km) allowing a constraint of the tail's skyplane linear extent. A power law was fit to the tail's surface-brightness profile, yielding $I(\rho) \propto \rho^{-1.1 \pm 0.003}$, where ρ is the skyplane project linear distance away from the nucleus.

The short-lived, impulsive nature of the outburst indicates that the tail of RS61 is reflective of a single Finson-Probstein (F-P) synchrone (i.e., a contour of β values for grains emitted at the same time) [80, 81]. A one-to-one mapping of β -vs- ρ was modeled to constrain the particle size distribution of the ejected dust grains. Results of the F-P analysis based on the HST data are shown in Fig. 5c, where the synchrone is shown with a color map reflecting the β -vs- ρ mapping. For the F-P analysis, the 2 m s^{-1} ejection speed was assumed to represent the initial grain speeds in the sunward direction. The β values along the dust tail span a narrow range between 0.038-0.25, where the bounds represent β values for larger grains near the nucleus to the smallest grains at the edge of the tail, respectively.

The F-P β values are inversely related to the grain sizes. Assuming spherical grains, β can be used to calculate the grain radius using $a = (C_\beta Q_{pr})/(\beta \rho_d)$, where ρ is the grain density, $C_\beta = 5.77 \times 10^{-4} \text{ kg m}^{-2}$ is a collection of constants representing effects of the Sun's gravity and solar radiation pressure, and Q_{pr} is the scattering efficiency

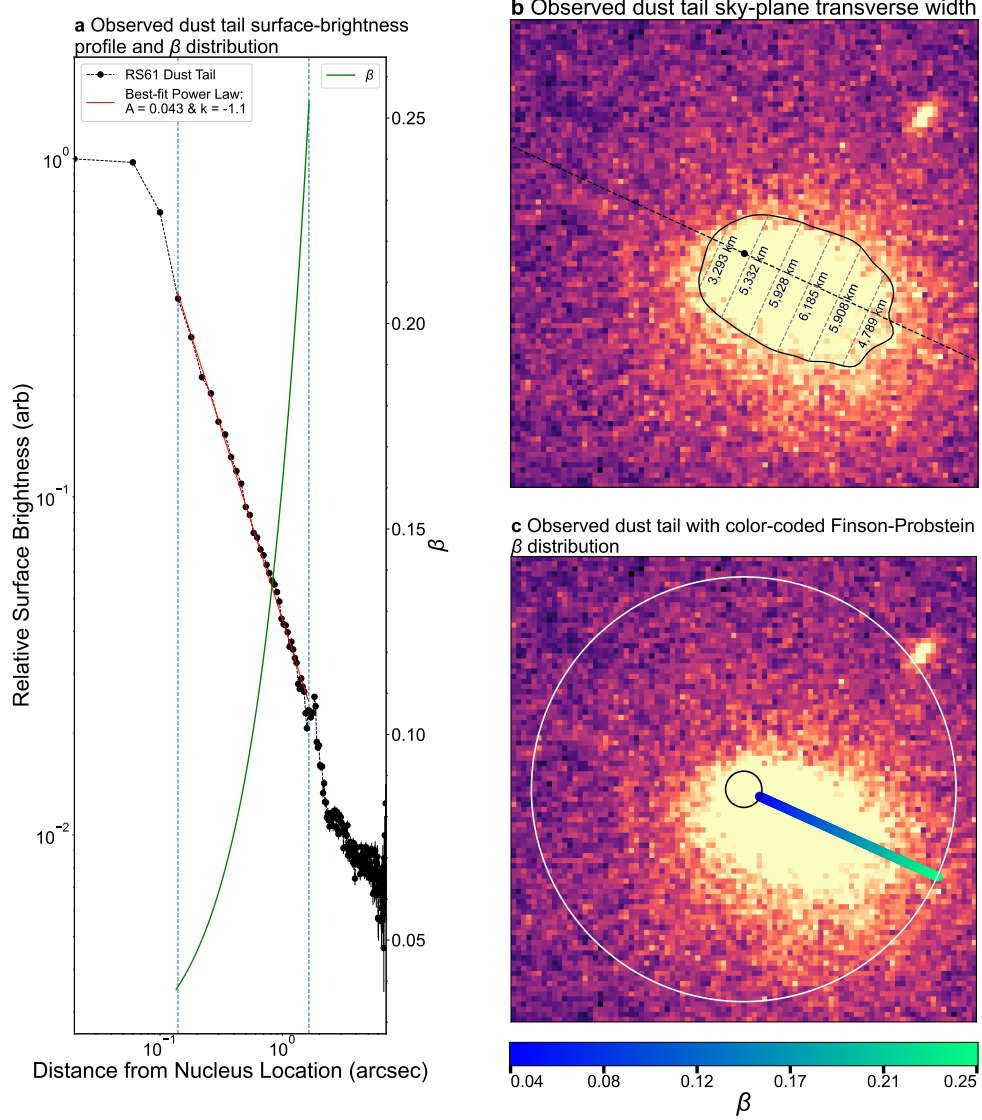


Fig. 5 The high-resolution HST data of the outburst coma enabled fitting dynamic models to estimate the energetics of the event and the physical properties of dust grains. **a** The surface brightness along the tail is displayed where regions with three distinct regions identified that correspond to the dust tail that follows a $I(\rho) \propto \rho^{-1.1}$ power-law, a steeper drop off at the tail's edge, and a residual background level. The two vertical dashed lines indicate the region dominated by the outburst dust grains along the tail that extends to $\sim 1''.75$ away from the nucleus. **b** A contour of surface brightness at the tail's outer edge was used to determine the spatial extent of the dust grains perpendicular to the tail direction and estimate their emission speed of $\sim 2 \text{ m s}^{-1}$. **c** A Finson-Probstein analysis is displayed with a synchrotron of β values overlaid. Panel **a** displays the β values along the tail's surface brightness that was used to constrain an average mass-weighted grain radius of $\sim 10 \pm 1 \mu\text{m}$.

of the grain from radiation pressure [79, 81]. For typical grain sizes seen in tails, on the order of several tens of μm , $Q_{pr} \approx 1$ [81, 82]. With these assumptions, the β -vs- ρ relation was transformed into a grain radius a -vs- ρ mapping.

The measured tail surface-brightness profile $I(\rho)$ was used with the modeled $a(\rho)$ profile to estimate the mass-weighted grain size of the outburst coma. Because the surface-brightness profile traces cross-sectional area to first order, while the mass per cross section scales with the grain size, the mass contributed by grains associated with a small interval $d\rho$ along the tail can be calculated using

$$dM(\rho) \propto I(\rho)a(\rho)d\rho. \quad (1)$$

Using this, the mass-weighted average grain size is

$$\langle a \rangle_M = \frac{\int a(\rho)dM(\rho)}{\int dM(\rho)} = \frac{\int I(\rho)a(\rho)^2d\rho}{\int I(\rho)a(\rho)d\rho}. \quad (2)$$

For RS61's outburst coma the mass-weighted average grain size was estimated to be $10 \pm 1 \mu\text{m}$.

We next measured the total brightness of the coma from the HST data to estimate the total effective cross section of the outburst coma. Flux contributions from the nucleus were estimated and removed from the coma's photometry measurement. For this subtraction we assumed a nucleus effective spherical radius of $5 \pm 1 \text{ km}$, a nucleus geometric albedo of $p_n = 0.05 \pm 0.02$ [83], and a linear phase law coefficient of 0.047, following the methods presented in [84]. A $m = 19.05 \pm 0.03 \text{ mag}$, in HST STMAG units [85], was measured from photometry using a $1.8''$ radius aperture centered on RS61's nucleus location, with an annulus with inner and outer radii of $4.0''$ and $6.0''$ being used to estimate the background for its subtraction. The nucleus radius and albedo uncertainties dominate the coma dust photometry measurement.

The dust coma's measured brightness was used to estimate the total dust cross-sectional area using Equation 2 from [84]. For this calculation, the Sun's magnitude in the F350LP filter (-26.51) was simulated using the software `synphot` [86]. The total effective cross-sectional area was measured to be $1.9 \pm 0.8 \times 10^9 \text{ m}^2$, assuming the dust grains have a geometric albedo of $p_d = 0.05 \pm 0.02$. Using the mass-weighted average grain radius yields an estimate of the total ejecta mass of $2.6 \pm 0.9 \times 10^7 \text{ kg}$. This mass corresponds to the total excavation of a cylindrical pit with a diameter and depth of approximately 45 m and 33 m, respectively, assuming a depth-to-width ratio of 0.75 [64, 87] and a bulk density of 500 kg m^{-3} [65] while the material was incorporated in the nucleus.

There are at least three alternative processes capable of producing the outburst: impacts, pit-forming events, and landslides [88, 89]. An impact by a small, $\sim 10 \text{ m}$ asteroid could excavate a similar material volume as seen on RS61, but such an event is extremely unlikely due to the low space density of small bodies at RS61's current heliocentric distance [e.g., 90]. A landslide would produce less overall ejecta due and a shorter-lasting outburst [88] than was observed. Due to the volume of the material measured in the coma, we conclude that a pit-forming event is the more likely culprit that caused the outburst.

The crystallization of amorphous water ice (AWI), an exothermic process, has been proposed as a mechanism capable of creating sinkhole-like cometary pits at heliocentric distances beyond Jupiter’s orbit [16, 91]. There are no features in RS61’s spectrum that suggest the presence of abundant water ice, however, so an alternative process may be required. Additionally, even if abundant AWI were present in the nucleus of RS61, the pit depth, likely the sub-surface depth where the outburst originated ($\sim 50\text{--}60$ K at a depth of 33 m), was at a temperature too cold for the crystallization process to occur on sufficiently rapid timescales. Therefore, we conclude that AWI crystallization does not explain the outburst and that the sublimation of a hypervolatile ice reservoir, such as CO, methane (CH_4), or even ethane (C_2H_6), is the most likely scenario for triggering the observed outburst.

Orbital Evolution History

Thermodynamical modeling shows that a Centaur’s past orbital evolution through the giant planet region determines the extent of thermal processing its nucleus has undergone—and the resulting volatile depletion—which in turn shapes its cometary behavior [92, 93]. This behavior is unique to each Centaur due to the chaotic gravitational influences of the giant planets. Generally, the least thermally processed Centaurs are those that are dynamically new, meaning that their orbits have just recently evolved to be fully inside the Centaur region. In this paper we use the definition by [8], where Centaurs are objects with $5.2 \text{ au} < q < 30 \text{ au}$ and $5.2 \text{ au} < a < 30 \text{ au}$. Eventually Centaur perihelia evolve interior to Saturn’s orbit, where the nuclei experience many close planetary encounters and increased heating, and quickly evolve towards their JFC stage [92, 93].

We utilized the Bulirsch-Stöer numerical integrator, which is a part of the Mercury6 N-body integration package [94], to investigate the past orbital evolution of RS61. We have used the orbits of 8 planets as the major bodies, while RS61 was simulated as a massless particle with a baseline 30-day timestep, sufficiently precise to map the evolution of RS61’s orbit. To account for known orbital uncertainties of RS61 we have generated 50 orbital clones based on the best-fit orbit and its covariance matrix from the JPL Small Body Database².

Our results show that RS61’s orbit is currently undergoing a steady decrease in perihelion distance (Fig. 6a), which may be altering the overall per-orbit insolation the object receives, as well as the surface temperature during the perihelion passages following the change. The associated change in thermal environment can have a profound effect on the nucleus [93], and in this case has likely caused the outbursting episodes, which could become more frequent in the future as the object approaches perihelion in 2028.

We have ran a 0.5 Myr numerical integration using the same setup and 50 orbital clones accounting for the orbital uncertainties with a timestep of 10 years to map the long-term past evolution of RS61. Figure 6b shows that although the perihelion distance of all clones q has been preserved within a $7 \text{ au} < q < 11 \text{ au}$ interval, $\sim 55\%$ of clones had semi-major axis a larger than 20 au, and $\sim 30\%$ had $a > 30 \text{ au}$ 0.5 Myr ago. Our dynamical results thus show that RS61 is likely a dynamically new Centaur

²<https://ssd.jpl.nasa.gov/sbdb.cgi>

477 sourced from the Scattering disc population, supporting the spectral analysis high-
 478 lighting this body as an organic-type Eccentric TNO subclass [52]. We conclude that
 479 RS61 likely belongs to a small fraction of former Scattering disc objects originating in
 480 the Cold classical Kuiper belt [?].

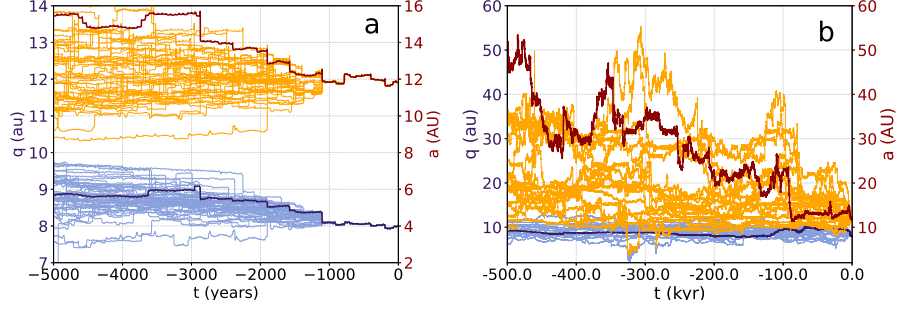


Fig. 6 The evolution of perihelion distance, q , (bottom) and semi-major axis, a , (top) of RS61 over the past 5 kyr (panel a) and 0.5 Myr (panel b). Dark red and blue lines indicates the evolution of nominal values, orange and light blue lines show the evolution of the orbital clone values of (a, q) respectively. The most decline trend in both perihelion and semimajor axis was caused by a close encounter with Saturn roughly 3000 years ago.

Data Availability

JWST and HST data are publicly available from the Space Telescope Science Institute’s Mikulski Archive for Space Telescopes at DOIs: <https://doi.org/10.17909/n71q-5e75> and <https://doi.org/10.17909/b66b-wa51>, respectively. Gemini images are publicly available from the Gemini Observatory Archive (<https://archive.gemini.edu/searchform>). Comet Chasers observations are publicly available from the LCO archive (<https://archive.lco.global>).

Acknowledgements

This work is based in part on observations made with the NASA/ESA/CSA James Webb Space Telescope. The data were obtained from the Mikulski Archive for Space Telescopes at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-03127 for JWST. These observations are associated with cycle 4 DD, programme #9481.

This research is based in part on observations made with the NASA/ESA Hubble Space Telescope obtained from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555. These observations are associated with cycle 32 GO, programme #18196.

Supporting observations were obtained by the Comet Chasers education and outreach programme (<https://www.cometchasers.org/>), led by Helen Usher, which is funded by the UK Science and Technology Facilities Council (via the DeepSpace2DeepImpact Project), the Open University and Cardiff University. It accesses the LCO telescopes through the Schools Observatory/Faulkes Telescope Project (TSO2025B-01 and TSO2026A-020) which is partly funded by the Dill Faulkes Educational Trust, and through the LCO Global Sky Partners Programme (LCOEPO2023B-013). Observers included Axel Bankole, James Bower, Eremis Maciulis, Oliver Roberts (participants on the British Astronomical Association’s Work Experience project), Quinn Sanger (BAA Back to Basics), Richard Miles (BAA) and representatives from the following schools and clubs: The Coopers’ Company and Coborn School, Upminster, UK; St Marys Catholic Primary School, Bridgend, UK; Institut d’Alcarràs, Catalonia, Spain; Louis Cruis Astronomy Club, Brazil; Model Junior High School of Heraklion, Greece; and Jelkovec High School, Zagreb, Croatia.

R.B., S.C., D.B.-M., A.G.-L. and O.P. gratefully acknowledge support from CNES (France) as part of their contributions to the JWST mission.

We thank N. Pinilla-Alonso and B. Holler for sharing the latest version of the DiSCo data. We are grateful to N. Pinilla-Alonso, J. Licandro and K. Volk for useful discussion and suggestions.

Pan-STARRS is supported by the NASA SSO Near-Earth Object Observations Programs 80NSSC18K0971 and 80NSSC21K1572. This research has made use of data and/or services provided by the IAU MPC.

Author contribution

E.L., PI of the observing proposals and the team, designed the observing campaign, mapped the orbital history of RS61, and provided overall leadership of the project. C.S. reduced and analyzed the JWST and HST data, performed the spectral extractions, completed the dust coma morphology analysis, and characterization of the dust grain physical properties. E.L. and C.S. contributed equally to this work. R.B., S.C. and D.B.-M. assisted with the interpretation of spectral signatures by providing context related to other JWST TNO and Centaur investigations and relevant laboratory measurements necessary to interpret the data presented. M.K. and A.G.-L. assisted with the interpretation of the outburst triggers. All authors contributed to the interpretation of the results and the preparation, writing and editing of the manuscript.

Funding

We acknowledge funding from the NASA SSO Prog. Id: #80NSSC23K1169 (PI: E. Lilly), from the STScI JWST-GO Proposal #09481 (PI: E. Lilly), and Prog. Id: #80NSSC23K0678 (PI: C. Schambeau).

Competing interests.

The authors declare no competing interests.

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