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Surface water-ice deposits in the northern shadowed regions of Ceres

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Supplementary Figure captions

Supplementary Figure 1 | Orbit of Ceres. This graph shows the prograde motion of Ceres around the sun in 1,682 days and includes key orbital elements: the line of apsides marks Ceres' closest ($q=2.56$ AU) and farthest ($Q=2.98$ AU) distances to the sun; the line of equinoxes denotes the day of equal light and darkness duration at the onsets of northern spring at solar longitude (L_s) 0° and northern autumn ($L_s=180^\circ$); solar longitudes 90° and 270° characterise northern and southern summer solstices, respectively; the dashed line highlights the line of intersection with the ecliptic plane and marks the positions where Ceres ascends above and descends below the ecliptic plane (Ω =ascending node). Red sections along Ceres' orbit below the ecliptic (dashed) mark the time periods where the first and last image in each orbit was taken (RC3—Rotation Characterisation 3; HAMO—High-Altitude Mapping Orbit; LAMO—Low-Altitude Mapping Orbit). Ceres passed the northern summer solstice on 22 July 2015, when the Dawn spacecraft was in transfer from Survey to HAMO.

Supplementary Figure 2 | Sketch of the Dawn mapping orbits around Ceres. This graph illustrates the spacecraft's four near-circular polar orbits: Rotation Characterisation 3 (RC3), Survey, High-Altitude Mapping Orbit (HAMO), and Low-Altitude Mapping Orbit (LAMO). For each orbit the orbital period and radius are given. Ceres itself (equatorial radius: 482 km; polar radius: 446 km) is shown at the centre. Figure is to scale. Lower right panel shows image footprints of two consecutive HAMO orbits (green), two orbits in LAMO (purple), and selected footprints in one Survey orbit. Note the increasing image overlap towards the north pole (centre) as well as the change in image extent on Ceres' surface as a function of spacecraft altitude. Latitudinal graticule is in 30° increments.

Supplementary Figure 3 | Assessment of light and shadow. (a) Relief and radiance cross section for a profile across a complex 39.2 km diameter crater located at $63.5^\circ\text{N}/52.5^\circ\text{E}$. The radiance profile is taken on Survey image 38,837 at local noon at $61.76^\circ\text{N}/51.14^\circ\text{E}$ (red spot) and is drawn along the azimuth of the sun (b). The exact same profile was taken on the HAMO digital terrain model (c). The radiance profile (a) exhibits two broad lows corresponding to the north-facing crater wall shadows. The shadow cast by the central peak appears narrow in the histogram. The broadest low (southern crater wall) is a type example of umbra (i.e., no direct sunlight is recorded). Solid and dashed lines represent the calculated lower and upper umbra threshold values, respectively (note the lines are not horizontal). Arrows mark the locations of the upper threshold and guide their respective positions along the topographic profile. (d-f) Projected, level-1B Survey image 38,837 (d) is binarised by applying the upper (e) and lower (f) threshold values. Red dot denotes the same location as in (b). The image sequence in (g) highlights illumination conditions of crater #2 on the last day of the Survey imaging campaign. The crater only hosts a small permanent shadow (two pixels each $400\text{ m} \times 400\text{ m}$) using the upper threshold criteria. Most of the lower north-facing crater wall appears to be in penumbra or is only partially illuminated where temperature is sufficiently low to cold-trap water molecules and to deposit water ice (cf. Fig. 4). The bright deposit where VIR spectra are acquired is only illuminated in the morning hours for c.3h. The numbers in the images denote local time (in Earth-hours; upper right) and image ID (lower right).

Supplementary Figure 4 | Local time chart along 65°N in 1°E longitude increments. The graph illustrates the approximate illumination conditions captured in Survey imagery and documents sufficient local time coverage at 65°N (and northwards). Black and white symbols denote darkness and daylight, respectively, at a given location at 65° northern latitude. Some locations are lit before and after sun rise/set and mark topographic highs (e.g., crater rims) whereas topographic lows (e.g., crater floors) receive only limited sun light during the day. Permanently shadowed regions would appear black over the course of 24h (e.g., at 132° and 312°E). Sun rise and sun set are calculated using the average (3.99°; $1\sigma=0.011$) sub-solar latitude (the solar declination) over the observed time period.

Supplementary Figure 5 | Local time chart along 83°N in 1°E longitude increments. The graph illustrates the approximate illumination conditions captured in HAMO data and documents sufficient local time coverage at 83°N (and northwards). Black and white symbols approximately denote darkness and daylight, respectively, at a given location at 83° northern latitude. Some locations are lit before and after sun rise/set and mark topographic highs (e.g., crater rims) whereas topographic lows (e.g., crater floors) receive only limited sun light during the day. Permanently shadowed regions would appear black over the course of 24h (here present at 23°E). Sun rise and sun set are calculated using the average (4.01°; $1\sigma=0.003$) sub-solar latitude (the solar declination) over the observed time period.

Supplementary Figure 6 | Shadow maps of the northern hemisphere of Ceres based on Survey images.

The top panel shows the averaged binary mosaic northward of 55°N at a resolution of 400 m/px with applied upper threshold value. Latitudinal graticule is shown for 65°N, 70°N, 80°N, and 83°N. The lower left and right panels show the binary maps with applied upper and lower threshold values, respectively. Permanent shadows are shown in black. The presented maps were prepared from 281 images with 179–222 image overlaps per pixel (on average 202 overlaps). Both maps are in stereographic projection centred at 90°N/0°E.

Supplementary Figure 7 | Shadow maps of the northern hemisphere of Ceres based on HAMO images.

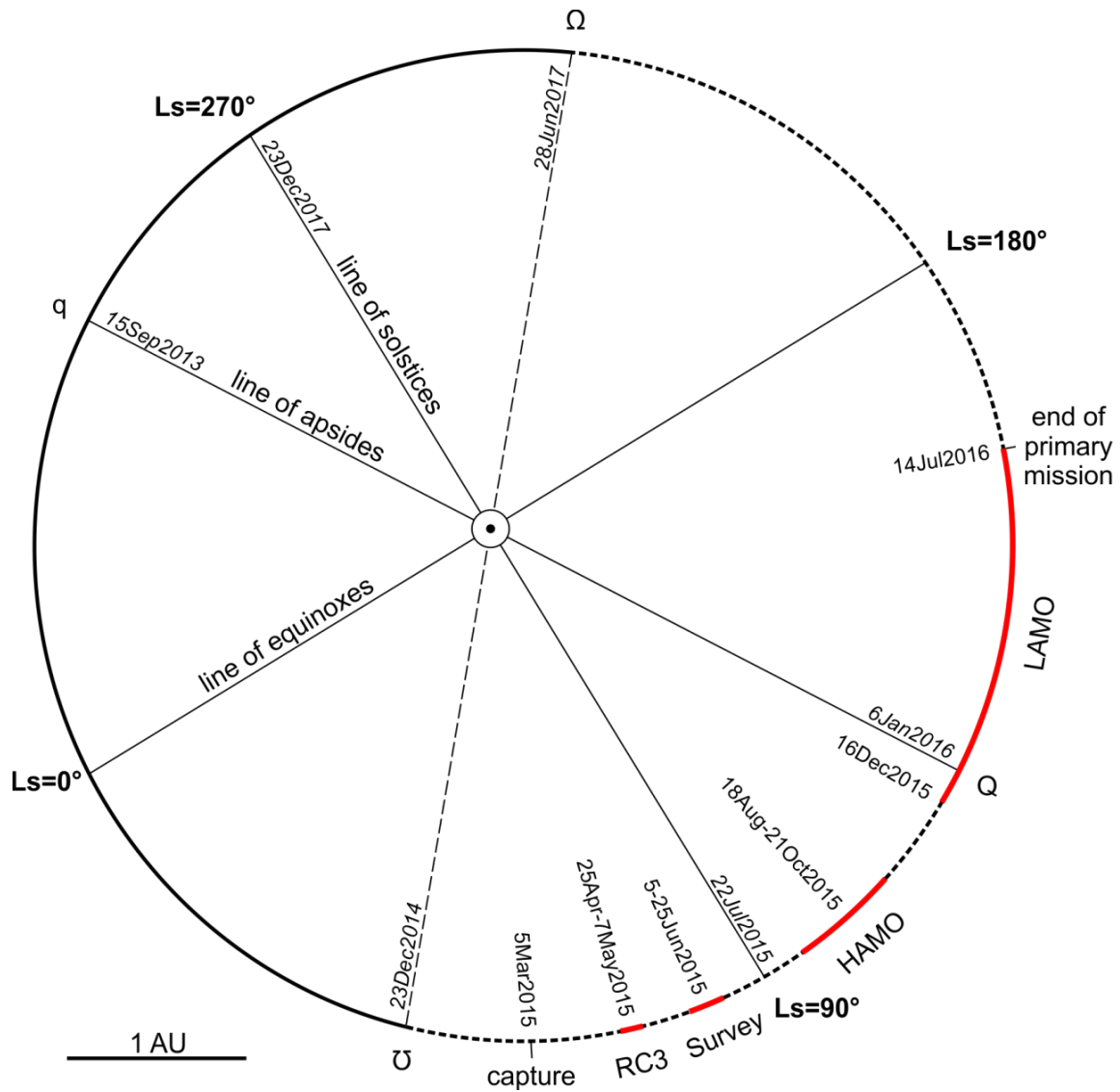
The top panel shows the averaged binary mosaic northward of 83°N at a resolution of 130 m/px with applied upper threshold value. Thin circle marks 85°N. The lower left and right panel show the binary maps with applied upper and lower threshold values; respectively. Permanent shadows are shown in black. The presented maps were prepared from 156 images with 96–136 image overlaps per pixel (on average 123 overlaps). Both maps are in stereographic projection centred at 90°N/0°E.

Supplementary Figure 8 | Compilation of craters hosting bright deposits. (a) moderately degraded, 4.7 km diameter crater (#3) located at 77.62°N/353.98°E exhibits a bright deposit at the periphery of the crater floor (b). Some small impact craters are observed on the crater floor material. Framing Camera (FC) image 59,335. (c) Moderately degraded, 3.1 km diameter crater (#4) located at 72.61°N/56.72°E. It contains a bright deposit on the pole facing lower slope of the crater wall (d). Impact craters on the crater floor and bright deposit materials are noted. FC image 46,446. (e) Fresh simple, 1.5 km diameter crater (#5; 81.49°N/216.52°E) hosts a small bright deposit (f) at its deepest portion. FC image 54,007. (g) The northern 0.7 km diameter crater (#6; 63.99°N/308.74°E) of a triple-paired crater chain, likely a secondary crater chain, accommodates a small bright deposit (h). FC image 59,812. (i) Moderately degraded 1.3 km simple crater (#7; 86.19°N/279.83°E) hosts a bright deposit on the lower pole facing crater wall (j). FC image 51,105. (k) Moderately degraded 2.5 km simple crater (#8; 80.10°N/173.05°E) with bright deposit on lower pole-facing crater wall (l). FC image 58,554. (m) Moderately degraded 2.7 km simple crater (#9;

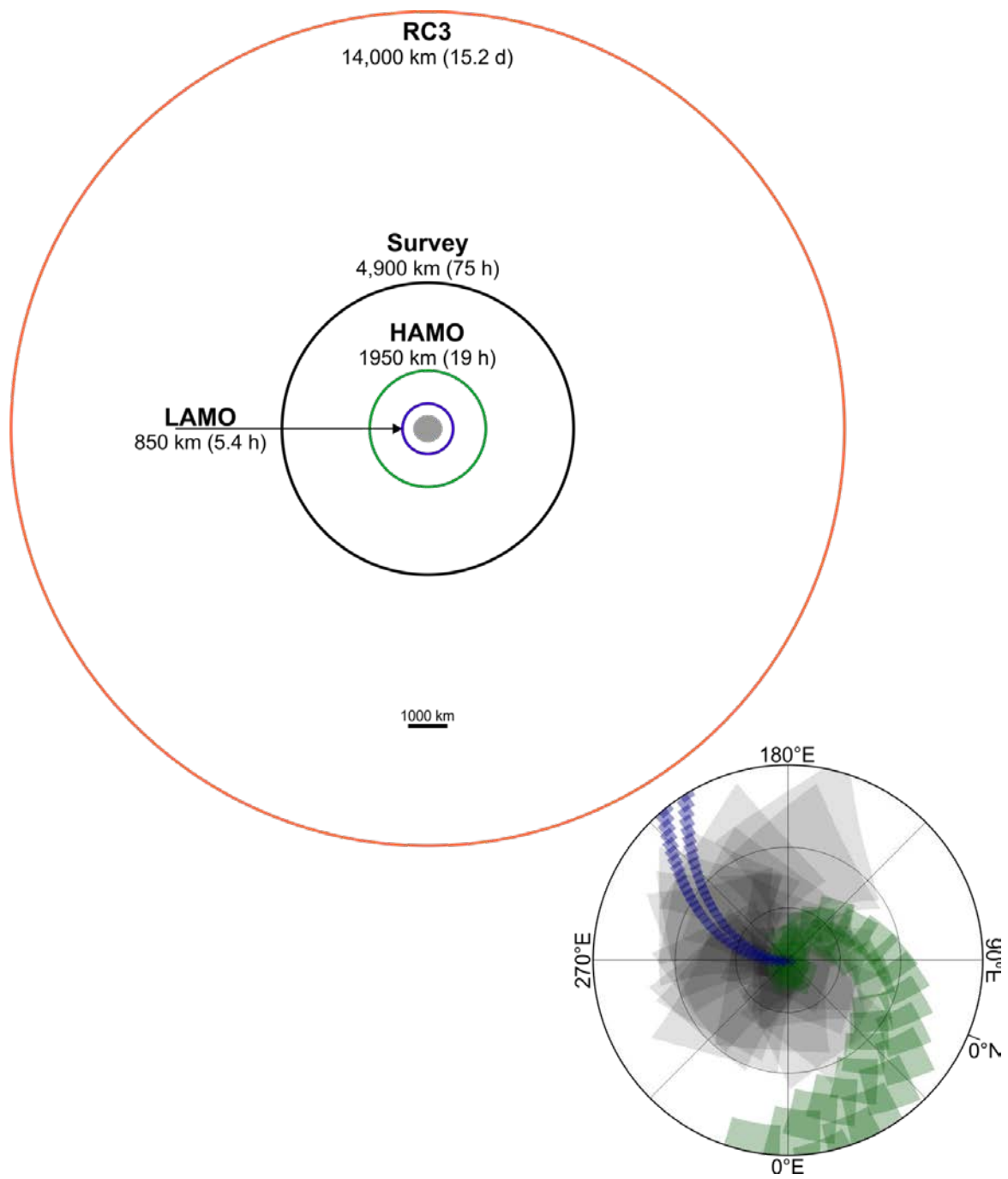
83.66°N/167.84°E) hosts a bright deposit on the lower pole-facing crater wall (**n**). FC image 59,983. Asymmetric crater ejecta distribution is noted. (**o**) Moderately degraded 2.4 km simple modified crater (#10; 78.16°N/167.62°E) with bright deposit on pole-facing lower to middle crater wall (**p**). FC image 58,554. (**q**) 3D anaglyph of crater #2 (see also **Fig. 3c-e**). Its fresh morphology and lack of superimposed craters on its ejecta blanket suggest a very recent formation age. (**r**) 3D anaglyph of the shadowed region of crater #2 (same viewing extent). It is apparent that the bright deposit is emplaced on crater wall material. The anaglyph is map-projected (orthographic projection centred at 69.9°N/114.0°E) and consists of FC images 46,607 and 50,776. All images (except (**q**) and (**r**)) are unprojected LAMO images; white arrows point to North. For each image pair the lower panel is shown at a magnification of factor 2 higher than the upper panel, except for (**q**) and (**r**), which are shown at the same scale.

Supplementary Table caption

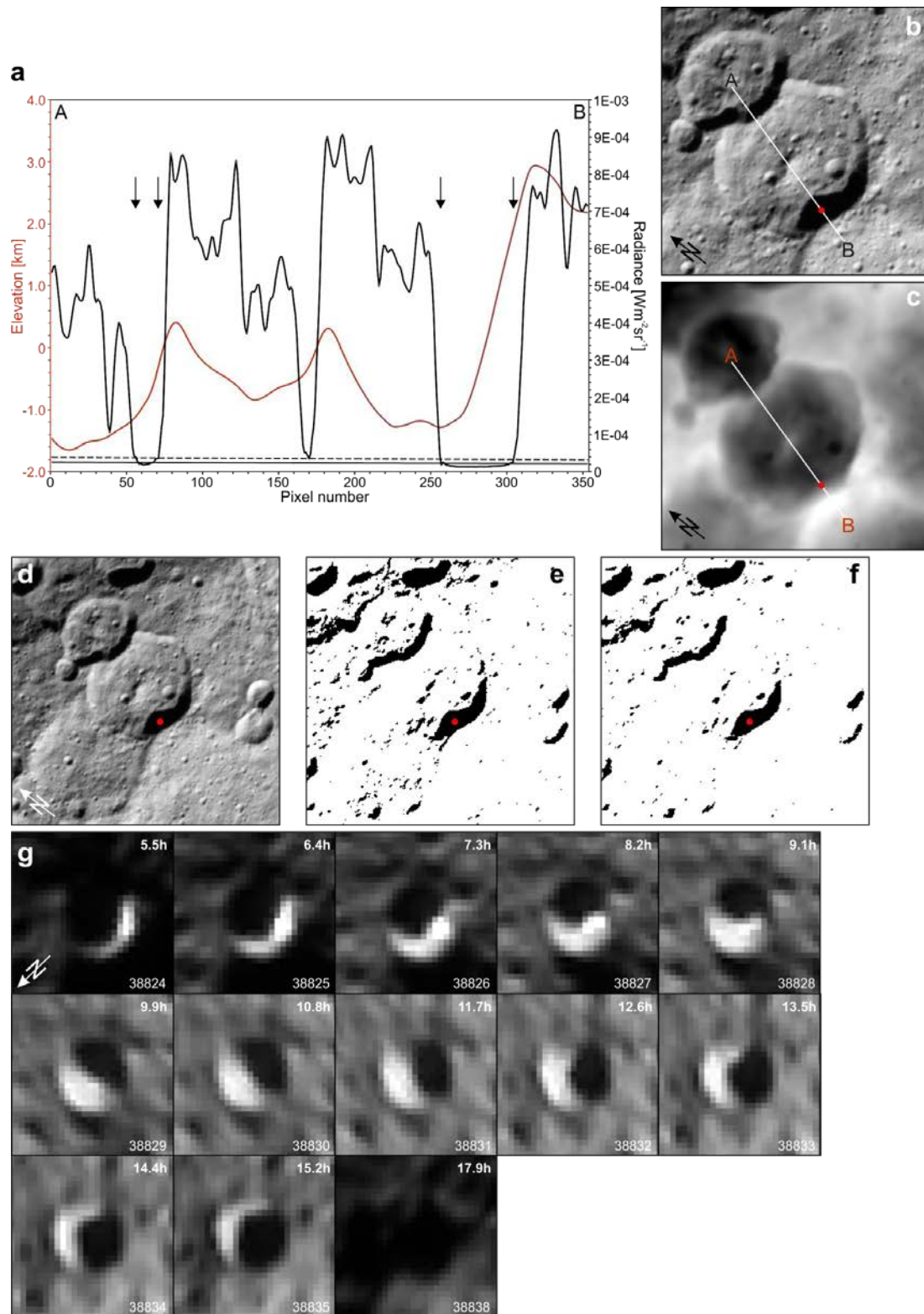
Supplementary Table 1 | Temperature results at impact crater centres. Permanent shadows do not exist in impact craters with depth-to-diameter ratios of 0.1 at incidence angles (*i*) of 69°.



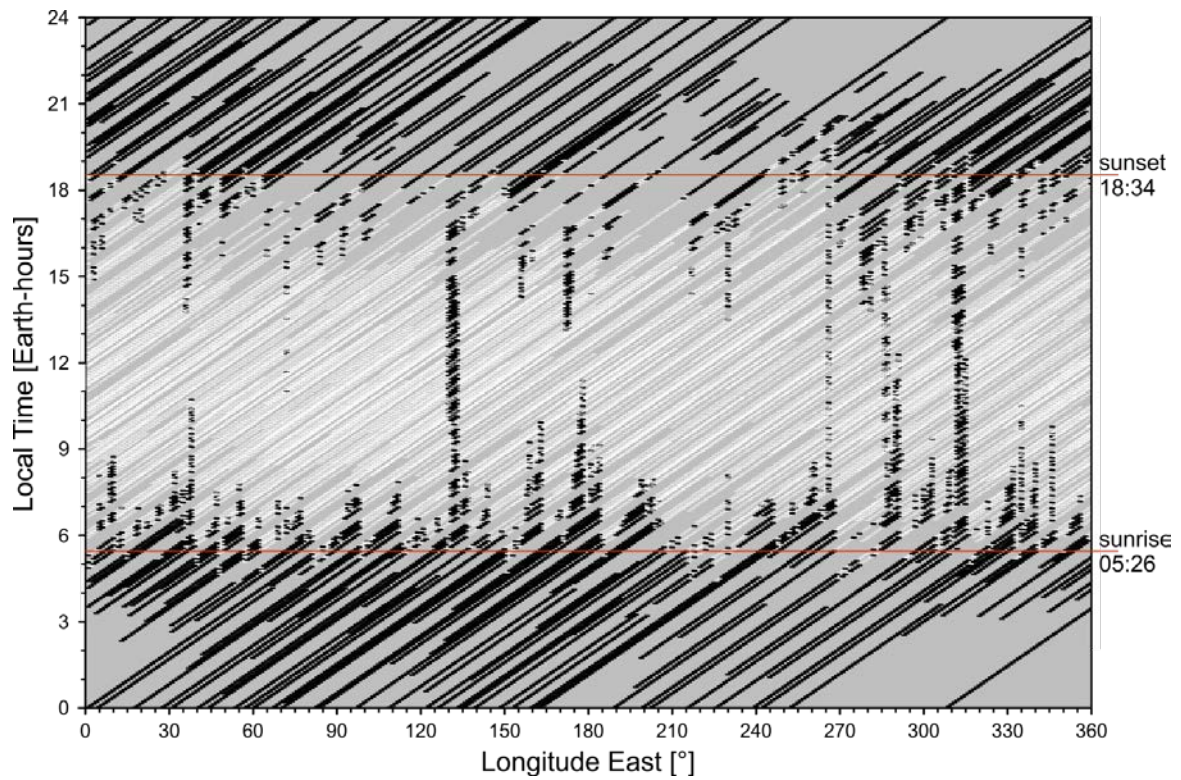
Supplementary Figure 1 | Orbit of Ceres.



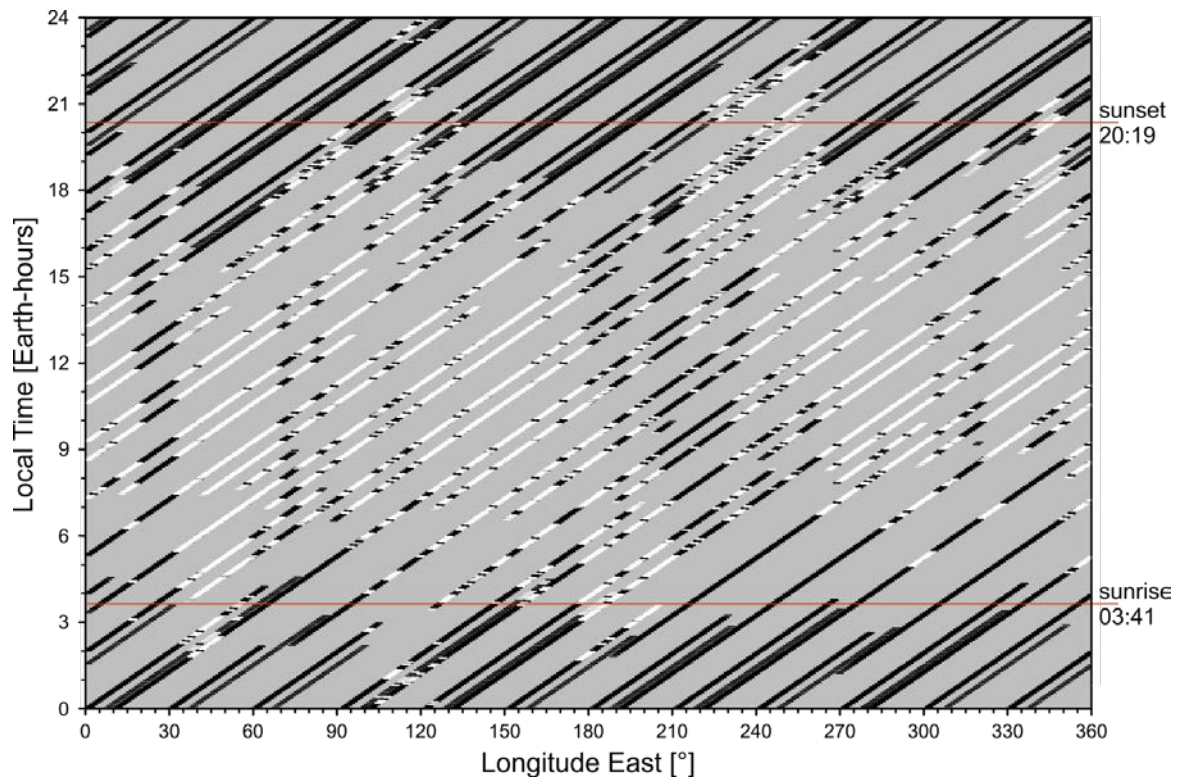
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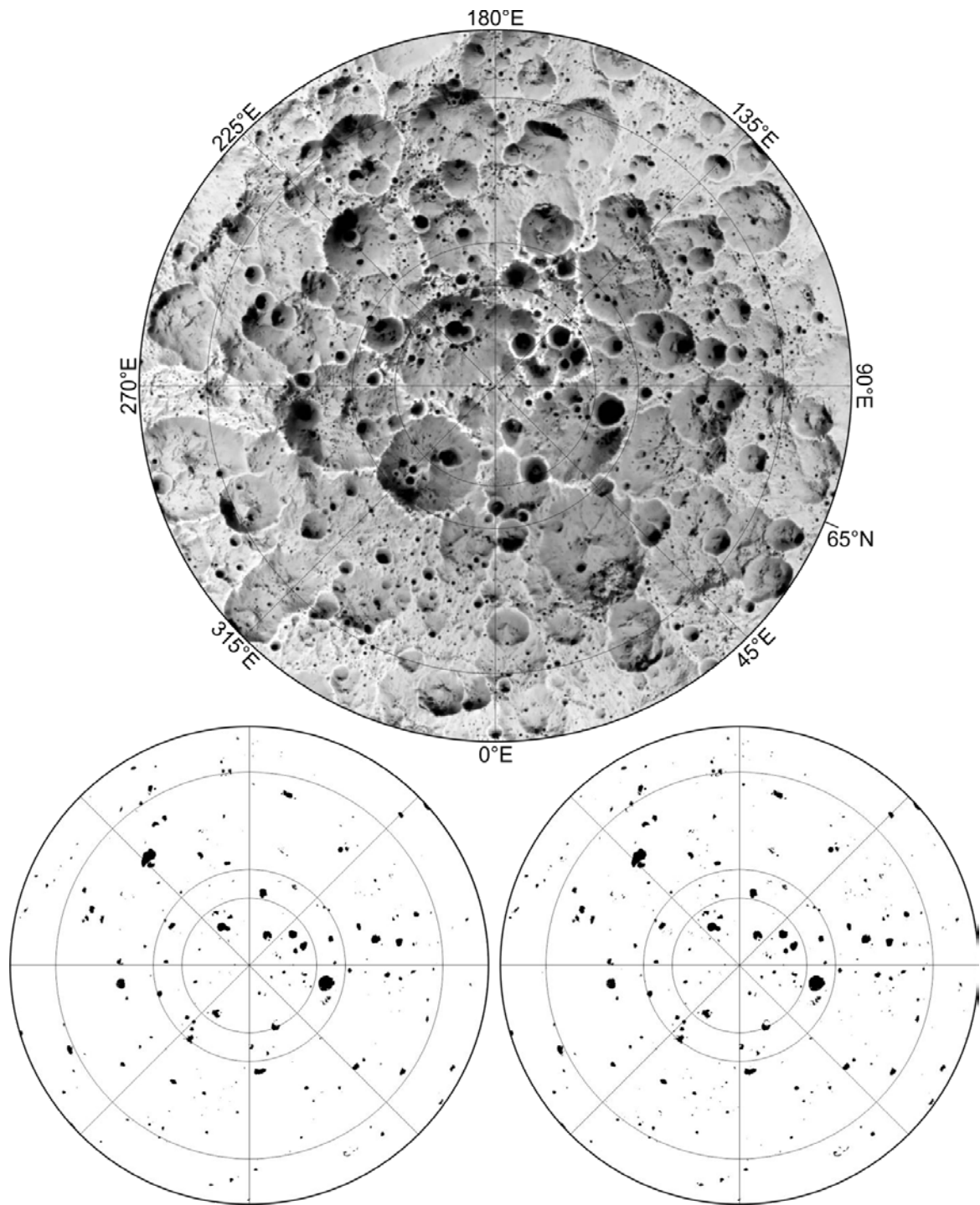
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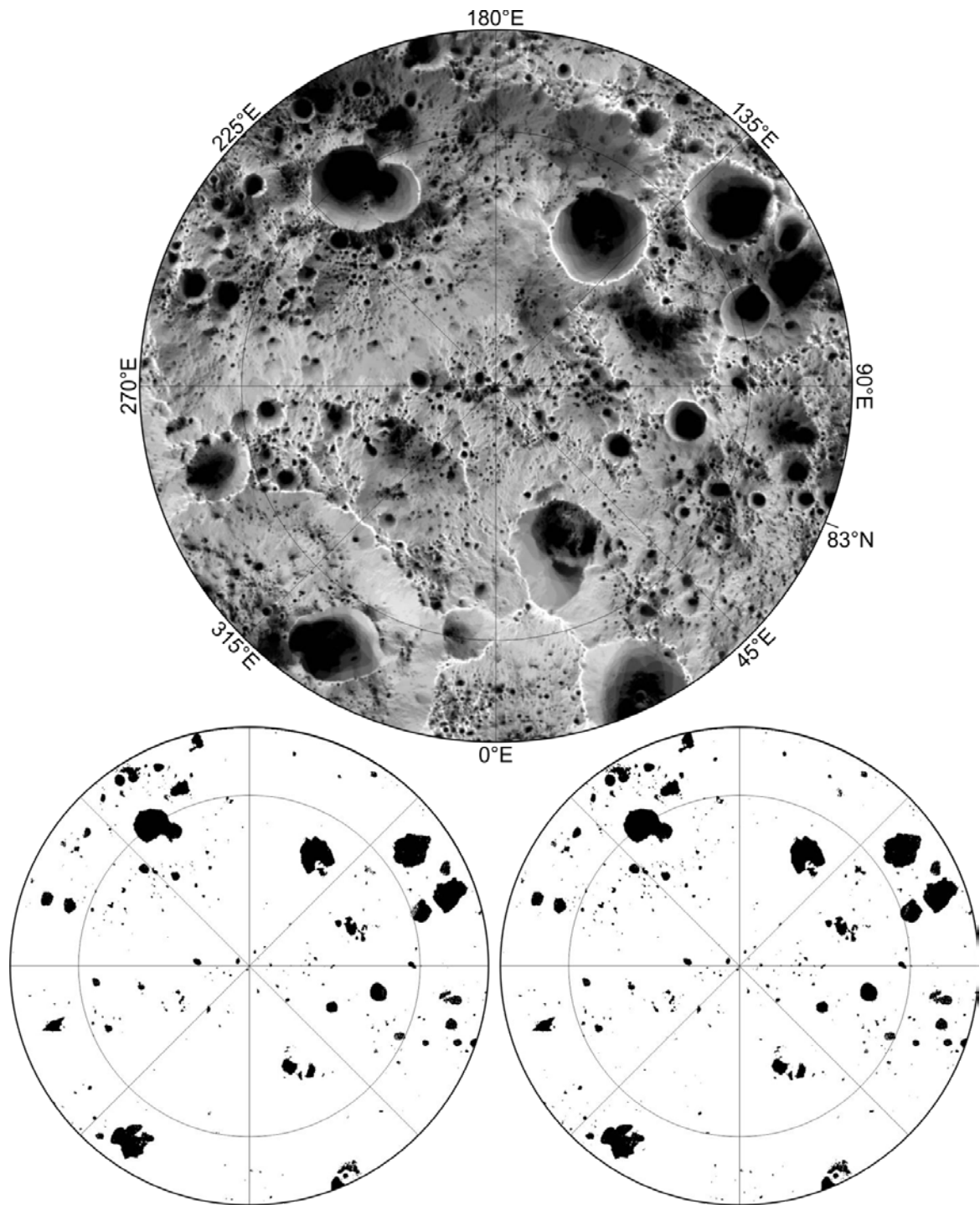
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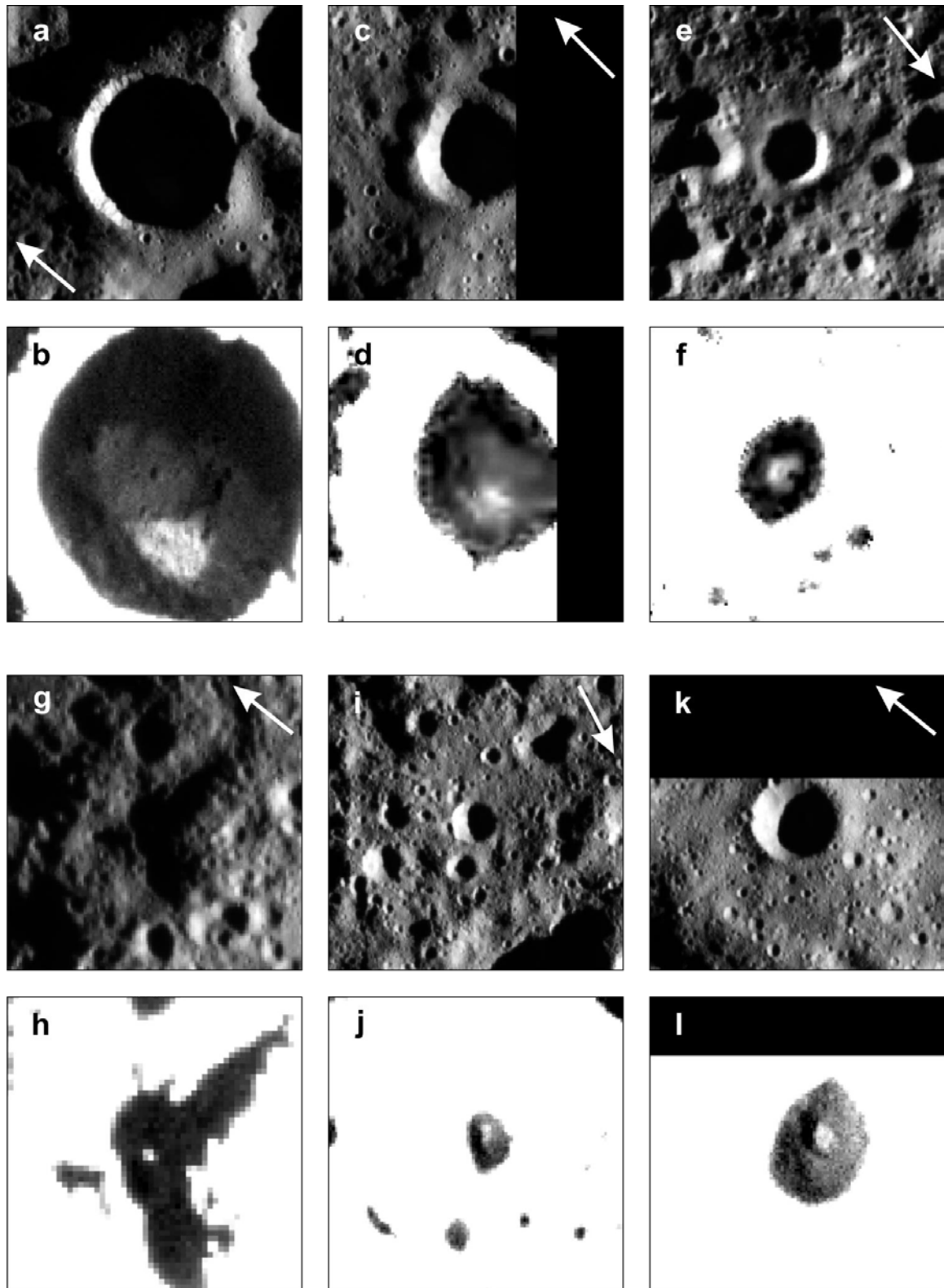
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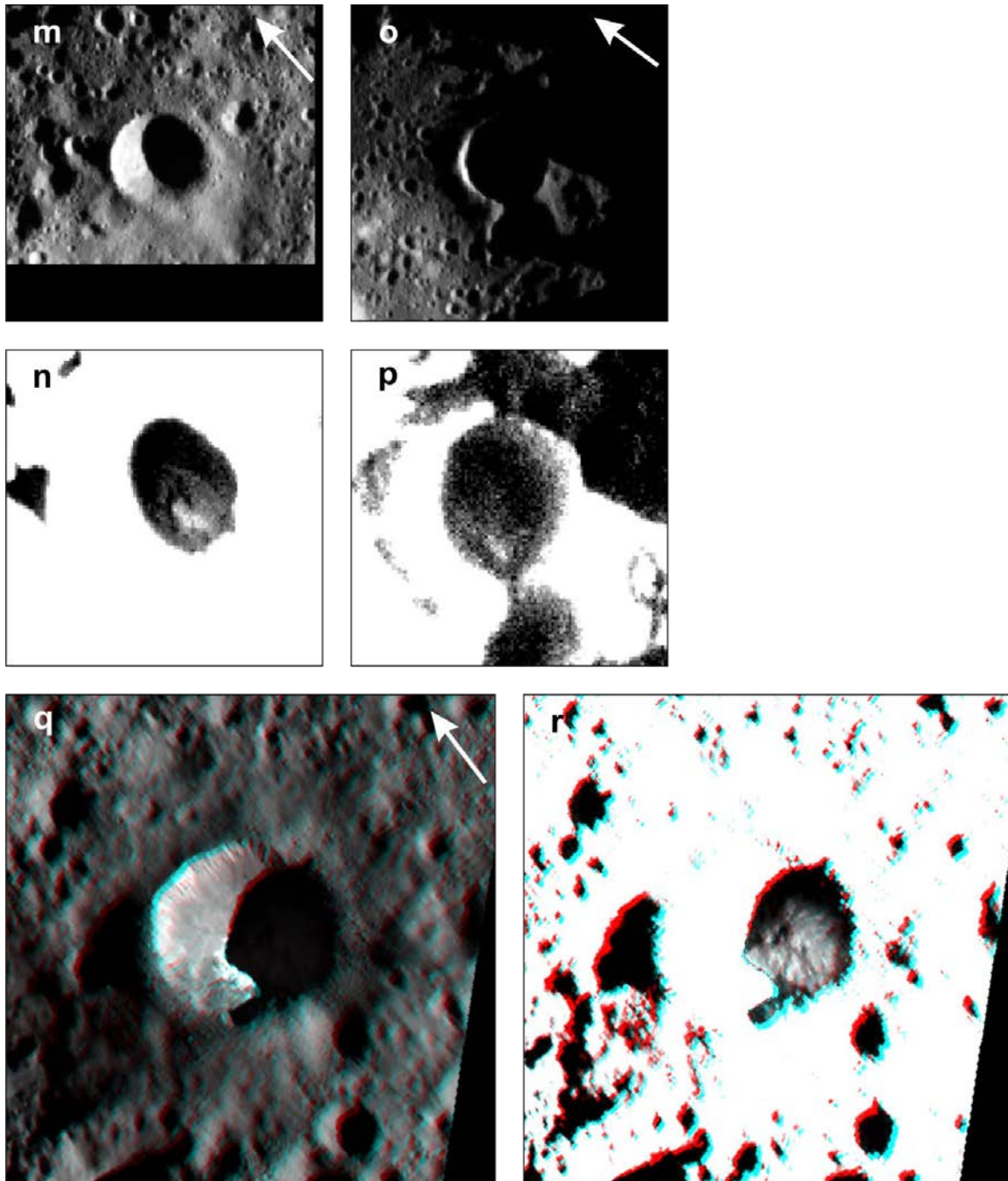
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Supplementary Figure 8 | Compilation of craters hosting bright deposits.



Supplementary Figure 8 | Compilation of craters hosting bright deposits. (*continued*)

Supplementary Table 1 | Temperature results at impact crater centres.

Crater Type	Depth/Diameter	T_{eq} when $i=86^\circ$	T_{eq} when $i=79^\circ$	T_{eq} when $i=69^\circ$
Bowl-Shaped	0.1	28K	37K	-
	0.2	35K	47K	57K
Flat-floored	0.1	32K	38K	-
	0.2	32K	45K	57K

Supplementary Videos captions

Supplementary Video 1 | Animation of Ceres' rotation viewed from RC3 orbit at a distance of approximately 13,650 km above Ceres' surface as acquired on 1 May 2015 (see **Supplementary Figure 2**). The changing illumination conditions of the northern hemisphere (50°-90°N) are illustrated here in 55 images for two rotations. At the beginning of the animation, the average map of 55 images is shown. The last two frames highlight shadowed region (black) in a binary map and an average binary map.

Supplementary Video 2 | Ejecta distribution of a 10-km impact crater at northern mid-latitude. This animation shows the impact of Oxo crater (42.2°N/359.6°E) where the projectile hits the surface at a speed of 4.6 km/s (average impact velocity on Ceres) at 45° (most probable impact angle) and target material is ejected symmetrically at 45° with respect to the local surface. Only those particles ejected at speeds ≥ 150 m/s are traced. High-velocity particles are distributed farther and can potentially re-impact (forming small secondary craters) at northern and southern polar latitudes. The ejecta distribution is asymmetric due to Ceres' high rotation rate of 9.07h. Re-impacted high-velocity particles can form secondary crater chains or elongated crater clusters, which is consistent with frequent small to large-scale chains and clusters observed at various locations on Ceres' surface. The simulated particle density is also a measure of impact probability, i.e., the denser the particle cloud the more likely. The Survey base map is in simple cylindrical projection centred at 0°N/0°E.