

A permanent, asymmetric dust cloud around the Moon

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Interplanetary dust particles hit the surfaces of airless bodies in the Solar System, generating charged¹ and neutral² gas clouds, as well as secondary ejecta dust particles³. Gravitationally bound ejecta clouds that form dust exospheres were recognized by *in situ* dust instruments around the icy moons of Jupiter⁴ and Saturn⁵, but have hitherto not been observed near bodies with refractory regolith surfaces. High-altitude Apollo 15 and 17 observations of a 'horizon glow' indicated a putative population of high-density small dust particles near the lunar terminators^{6,7}, although later orbital observations^{8,9} yielded upper limits on the abundance of such particles that were a factor of about 10^4 lower than that necessary to produce the Apollo results. Here we report observations of a permanent, asymmetric dust cloud around the Moon, caused by impacts of high-speed cometary dust particles on eccentric orbits, as opposed to particles of asteroidal origin following near-circular paths striking the Moon at lower speeds. The density of the lunar ejecta cloud increases during the annual meteor showers, especially the Geminids, because the lunar surface is exposed to the same stream of interplanetary dust particles. We expect all airless planetary objects to be immersed in similar tenuous clouds of dust.

The Lunar Atmosphere and Dust Environment Explorer (LADEE) mission was launched on 7 September 2013. After reaching the Moon in about 30 days, it continued with an instrument checkout period of about 40 days at an altitude of 220–260 km. LADEE began its approximately 150 days of science observations at a typical altitude of 20–100 km, following a near-equatorial retrograde orbit, with a characteristic orbital speed of 1.6 km s^{-1} (ref. 10). The Lunar Dust Experiment (LDEX) began its measurements on 16 October 2013 and detected a total of approximately 140,000 dust hits during about 80 days of cumulative observation time out of 184 total days by the end of the mission on 18 April 2014. LDEX was designed to explore the ejecta cloud generated by sporadic interplanetary dust impacts, including possible intermittent density enhancements during meteoroid showers, and to search for the putative regions with high densities of $0.1\text{-}\mu\text{m}$ -scale dust particles above the terminators. The previous attempt to observe the lunar ejecta cloud by the Munich Dust Counter on board the HITEN satellite orbiting the Moon (15 February 1992 to 10 April 1993) did not succeed, owing to its distant orbit and low sensitivity¹¹.

LDEX is an impact ionization dust detector (Methods subsection 'The LDEX instrument'). When pointed in the direction of motion of the spacecraft, LDEX recorded average impact rates of about 1 and about 0.1 hits per minute of particles with impact charges of $q \geq 0.3$ and $q \geq 4 \text{ fC}$, corresponding to particles with radii of $a \gtrsim 0.3 \text{ }\mu\text{m}$ and $a \gtrsim 0.7 \text{ }\mu\text{m}$, respectively (Fig. 1). Approximately once a week, LDEX observed bursts of 10 to 50 particles in a single minute. Particles detected in a burst are most likely to originate from the same well-timed and well-positioned impact event that happened just minutes before their detection on the ground-track of LADEE. Several of the

yearly meteoroid showers generated sustained elevated levels of LDEX impact rates, especially those where the majority of the incoming meteoroids hit the lunar surface near the equatorial plane, greatly enhancing the probability of LADEE crossing their ejecta plumes. The Geminids generated the strongest enhancement in impact rates for ± 1.5 days centred around 14 December 2013.

The distribution of the detected impact charges remained largely independent of altitude, and throughout the entire mission it closely followed a power law: $p_q(q) \propto q^{-(1+\alpha)}$ (Fig. 2). This alone indicates that the initial mass distribution of the ejecta particles is, to a good approximation, independent of their initial speed and angular distributions (Methods subsection 'Dust ejecta clouds'), and that the number of ejecta particles generated on the surface per unit time with mass greater than m follows a power law: $N^+(\geq m) \propto m^{-\alpha}$. The LDEX measurements indicate $\alpha \approx 0.9$, surprisingly close to the value $\alpha_G = 0.8$ suggested by the Galileo mission at the icy moons of Jupiter¹²

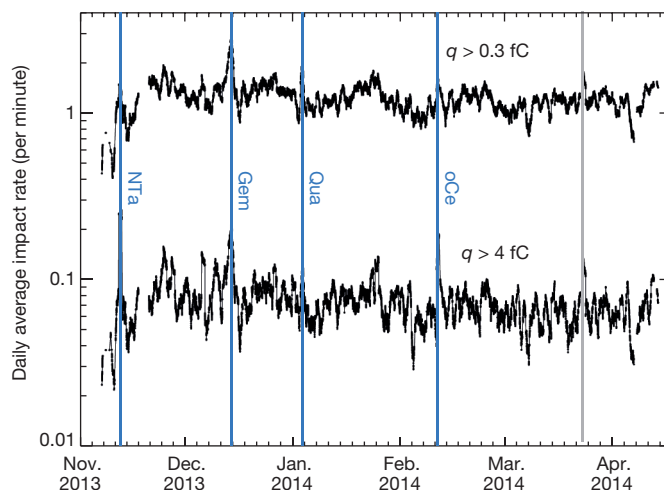


Figure 1 | Impact rates throughout the mission. The daily running average of impacts per minute of particles that generated an impact charge of $q \geq 0.3 \text{ fC}$ (radius $a \gtrsim 0.3 \text{ }\mu\text{m}$) and $q \geq 4 \text{ fC}$ (radius $a \gtrsim 0.7 \text{ }\mu\text{m}$) recorded by LDEX. The initial systematic increase until 20 November 2013 is due to transitions from the high-altitude checkout to the subsequent science orbits. Four of the several annual meteoroid showers generated elevated impact rates lasting several days. The labelled annual meteor showers are: the Northern Taurids (NTa); the Geminids (Gem); the Quadrantids (Qua); and the Omicron Centaurids (oCe). The observed enhancement peaking on 25 March 2014 (grey vertical line) does not coincide with any of the prominent showers. During the Leonids meteor shower around 17 November 2013, the instrument remained off due to operational constraints. From counting statistics, we determine that the daily average impact rate of particles generating a charge of at least 0.3 fC is 1.25 hits per minute and, hence, the 1σ relative error is about 2%, while for particles generating an impact charge $> 4 \text{ fC}$ the average rate is 0.08 hits per minute and, hence, the 1σ relative error is about 10%.

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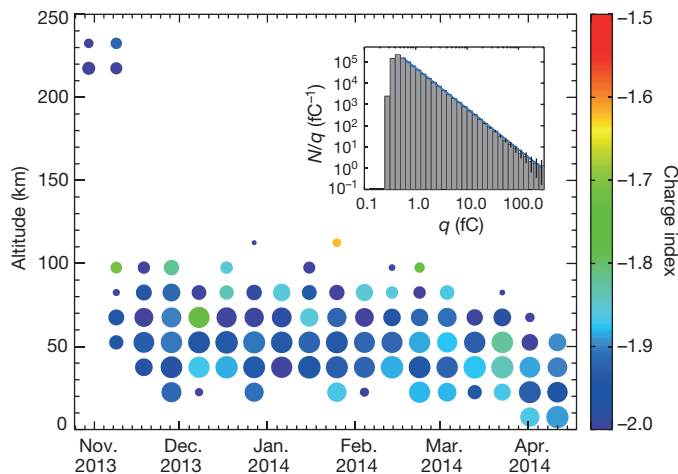


Figure 2 | Slope of the charge and mass distributions. The exponent of the power-law distributions of the impact charges $p_q(q) \propto q^{-(1+\alpha)}$ fitted to LDEX measurements as functions of altitude (15 km bins) and time (10 day bins). The colour indicates the value of the charge distribution index $-(1+\alpha)$, and the size of a circle is inversely proportional to its absolute uncertainty (largest circle: ± 0.1 ; smallest circle ± 0.5). The inset shows the impact charge distribution for all heights for the entire mission, resulting in a χ^2 minimizing fit²¹ of $\alpha = 0.910 \pm 0.003$.

and to laboratory experimental results of ejecta production from impacts¹³. The derived ejecta size distribution also represents the size distribution of the smallest lunar fines (very small particles) on the surface because most ejecta particles return to the Moon and comprise the regolith itself, unless these small particles efficiently conglomerate on the lunar surface into larger particles.

The characteristic velocities of dust particles in the cloud are of the order of hundreds of metres per second, which is small compared to typical spacecraft speeds of 1.6 km s^{-1} . Hence, with the knowledge of the spacecraft orbit and altitude, impact rates can be converted directly into particle densities as functions of time and position. This approach is expected to result in a relative error $< 20\%$, on the basis of a complete ejecta cloud model¹² (Extended Data Fig. 2). Both the derived average number density as a function of height, and the initial speed distribution match expectations only for altitudes $h \geq 50 \text{ km}$ (Extended Data Fig. 3). This indicates that, for the lunar surface, the

customary assumption of a simple power-law speed distribution with a single sharp cut-off minimum speed u_0 needs revision for speeds below about 400 m s^{-1} . At higher values the speed distribution follows a simple power law (Extended Data Table 1), as predicted by existing models¹². An ejecta plume opening cone angle of $\psi_0 \approx 30^\circ$ is consistent with our measurements, including those taken during the observed bursts of impacts. The average total mass of the dust ejecta cloud is estimated to be about 120 kg, approximately 0.5% of the neutral gas atmosphere¹⁴.

We found that the density distribution is not spherically symmetric around the Moon (Fig. 3), exhibiting a strong enhancement near the morning terminator between 5 and 7 h local time (LT), slightly canted towards the Sun from the direction of the motion of the Earth–Moon system about the Sun (6 LT). The observed anisotropy reflects the spatial and velocity distributions of the bombarding interplanetary dust particles (Extended Data Fig. 4) responsible for the generation of the ejecta clouds (Methods subsection ‘Dust production from impacts’). This observed anisotropy is in contrast to the roughly isotropic ejecta clouds engulfing the Galilean satellites, where the vast gravitational influence of Jupiter is efficiently randomizing the orbital elements of the bombarding interplanetary dust particles¹⁵. The anisotropic ejecta production is consistent with existing models of the interplanetary dust distributions near the Earth that combine *in situ* dust measurements, visible and infrared observations of the zodiacal cloud, as well as ground-based visual and radar observations of meteors in the atmosphere^{16,17}. The dust production on the lunar surface is dominated by particles of cometary origin, as opposed to slower asteroidal dust particles, which follow near-circular orbits as they migrate towards the Sun, owing to Poynting–Robertson drag¹⁸. Meteoroids that are of asteroidal origin would be able to sustain only a much weaker, more azimuthally symmetric ejecta cloud, contrary to LDEX observations.

In addition to bombardment by interplanetary dust, the exposure of airless surfaces to ultraviolet radiation and solar wind plasma flow could result in the lofting of small dust particles, owing to electrostatic charging and subsequent mobilization¹⁹. The charging processes are expected to be most efficient over the terminators, where strong localized electric fields could exist over the boundaries of lit and dark regions. High-altitude horizon glow observations near the lunar terminator suggested a population of grains, characteristically of radius $0.1 \mu\text{m}$, with a density of $n \approx 10^4 \text{ m}^{-3}$ at an altitude of $h = 10 \text{ km}$,

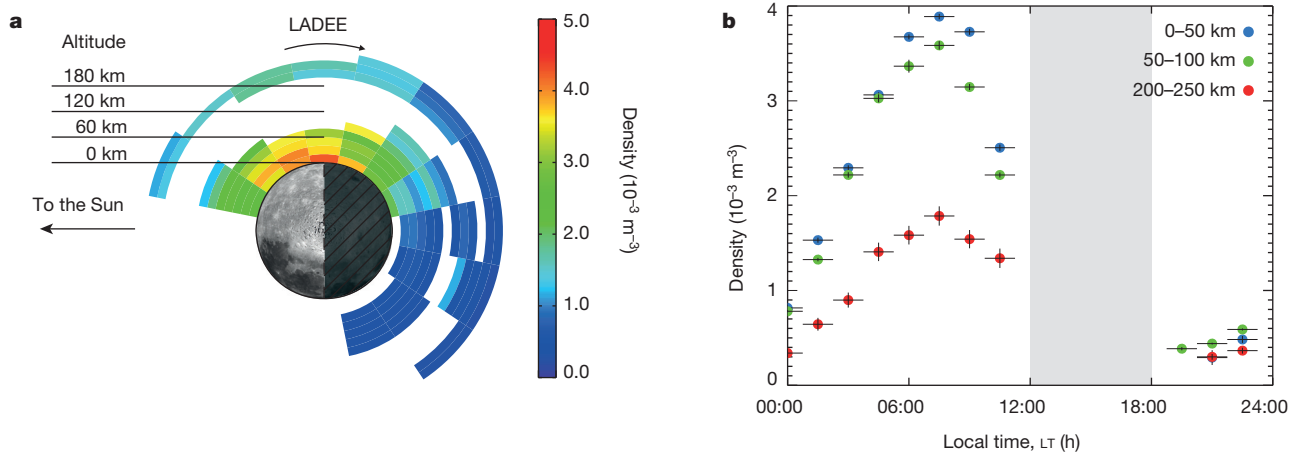


Figure 3 | Lunar dust density distribution. **a**, The top-down view of the dust density $n(a \geq 0.3 \mu\text{m})$ projected onto the lunar equatorial plane. While pointed near the direction of the motion of the spacecraft, LDEX did not make measurements between 12 and 18 LT. White colouring indicates regions where LADEE did not visit or was not set up for normal operations. **b**, The density as a

function of LT at three different altitude bins showing a persistent enhancement canted towards the Sun away from the direction of the orbital motion of the Earth–Moon system. Error bars were calculated by propagating the $\sqrt{N}$ error through the density calculation, where N is the number of detected dust impacts.

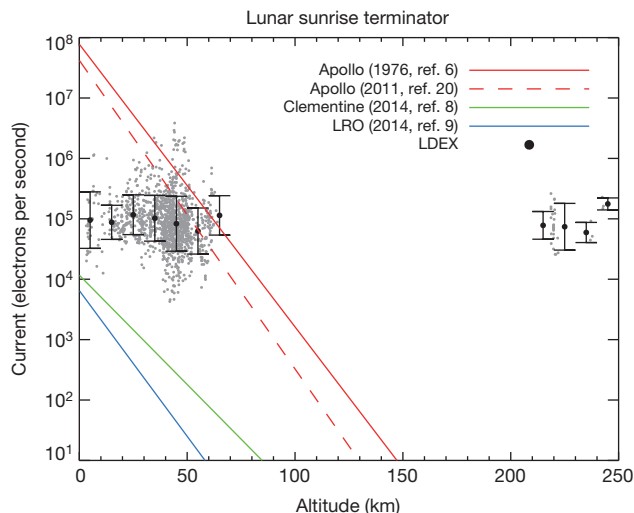


Figure 4 | LDEX current measurements. The accumulated charge collected by LDEX in $dt = 0.1$ s intervals (J_{dust}), averaged over the sunrise terminator between 5:30 and 6:30 LT. The coloured lines show the predicted value of J_{dust} based on the impacts of small particles alone using the upper limits of the dust densities estimated by remote sensing visible^{6,8,20} and ultraviolet⁹ observations. Error bars show 1σ on $\log J_{\text{dust}}$ as the current measurements are log-normally distributed. Because $J_{\text{dust}} \approx 10^5$ electrons per second is two orders of magnitude lower than the Apollo estimates near an altitude of 10 km and exhibits no altitude dependence, LDEX measurements show no evidence for the existence of the suggested relatively dense clouds of $0.1\text{-}\mu\text{m}$ -sized dust particles. LRO is the Lunar Reconnaissance Orbiter.

increasing towards the surface to $n = 5 \times 10^5 \text{ m}^{-3}$. Follow-up observations^{8,9} indicated a drastically lower upper-limit of the lofted dust densities. At an altitude of 10 km, our dust current measurements show an upper limit for the density of particles of radius $0.1 \mu\text{m}$ that is approximately two orders of magnitude below the Apollo estimates²⁰. However, the LDEX dust current measurements (Methods subsection ‘The LDEX instrument’) of $J_{\text{dust}} \approx 10^5$ electrons per second (Fig. 4) remained independent of altitude and, hence, gave no indication of the relatively dense cloud of $0.1\text{-}\mu\text{m}$ -sized dust that was inferred from the Apollo observations over the lunar terminators.

Online Content Methods, along with any additional Extended Data display items and Source Data, are available in the online version of the paper; references unique to these sections appear only in the online paper.

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Author Contributions M.H. was the instrument principal investigator, directed the data analysis, and was primarily responsible for writing this paper. J.R.S. developed the data analysis software. S.K. was responsible for the calibration of the instrument and contributed to the data analysis. J.S. led the modelling effort. E.G. and R.S. contributed to the analysis and interpretation of the data. Z.S. designed the instrument and contributed to the data analysis.

Author Information Reprints and permissions information is available at www.nature.com/reprints. The authors declare no competing financial interests. Readers are welcome to comment on the online version of the paper. Correspondence and requests for materials should be addressed to M.H. (horanyi@colorado.edu).

METHODS

The LDEX instrument. The Lunar Dust Experiment (LDEX) is an impact ionization dust detector, which measures both the positive and negative charges of the plasma cloud generated when a dust particle strikes its target²². The amplitude and shape of the waveforms (signal versus time) recorded from each impact are used to estimate the mass of the dust particles. The instrument has a total sensitive area of 0.01 m², which gradually decreases to zero for particles arriving from outside its dust field-of-view of $\pm 68^\circ$ off from the normal direction. LDEX is sensitive to ultraviolet; hence, its operations, in general, excluded the Sun in its optical field-of-view of $\pm 90^\circ$.

Particles below the single impact detection threshold generate a plasma cloud in the same way as larger impacts, but without triggering a full waveform capture. Their collective signal is integrated independently of the impacts of large particles. In addition to small dust particles, the integrated ion signal is also sensitive to a number of possible background contributions, most importantly ultraviolet photons scattering into the ion detector, generating photoelectrons. To identify the background contributions in the collective signal, the acceleration potential between the target and ion collector is intermittently switched from its nominal -200 V to $+30$ V, making the instrument 'blind' to dust. The contributors to the current in nominal mode (J_N) are ions from dust impacts, photoelectrons and low- and high-energy ions. In switched mode (J_S) the contributors are photoelectrons and high-energy ions. High energy in this case indicates >30 eV, as these ions can reach the microchannel plate even in switched mode. Hence, the difference $J_N - J_S$ represents the collective signal of small dust particles and low-energy ions only. Each dust particle with a radius of $0.1 \mu\text{m}$ and impact speed of 1.6 km s^{-1} is expected to generate²³ $Q_i \approx 100e$. Their collective current is $J_{\text{dust}} \approx AvnQ_i$, where A is the detector sensitive area, v is the speed of dust particle relative to the spacecraft, and n is the density of the small particles. Hence, attributing $J_N - J_S$ to small dust particles alone allows us to set an upper limit for n . Alternatively, estimates for n from independent observations can be used to predict J_{dust} , which we can then compare to our measurements. The low-energy ion contribution may be due to back-scattered solar wind protons²⁴, energetic neutral atoms^{25,26} and the lunar ionosphere²⁷. Any contribution of low-energy ions to $J_N - J_S$ would further reduce our estimate of n .

Dust ejecta clouds. We compare the steady state, spherically symmetric model of a dust cloud¹² to the LT-averaged LDEX observations. The phase space density of dust above the surface based on a model for an impact-generated ejecta cloud can be written as^{12,28}

$$n(v, \theta, \phi; r) = \frac{N^+}{8\pi^2 R r} \frac{f_u(u(v)) f_\psi(\psi(v, \theta))}{v u(v)^2 \sin \theta \cos \psi(v, \theta)} \quad (1)$$

Here, the variables v, θ, ϕ denote the velocity vector of dust grains at a radial distance r from the Moon (lunar radius $R = 1,737 \text{ km}$). The distance r is regarded as a parameter of the distribution, not a variable. Further, θ is the angle between the velocity vector and the radial direction and ϕ is the velocity azimuth angle (anti-clockwise around the radius vector). The distribution does not depend explicitly on ϕ for a spherically symmetric cloud. We retain the azimuthal dependence to perform averages over quantities that do depend on ϕ . N^+ is the total rate of grains produced on the surface. We denote by u the starting speed of ejecta on the surface and by ψ the ejection cone angle measured from the surface normal. Using the conservation of energy and angular momentum of the two-body problem we have $\psi = \psi(v, \theta)$ and $u = u(v)$. For the distribution of starting velocities, f_u , we use a power law with exponent μ (equivalent to $\gamma + 1$ in other customary notation¹²), normalized to unity in the range $u \in [u_0, \infty]$:

$$f_u(u) = \frac{\mu - 1}{u_0^{1-\mu}} u^{-\mu}$$

For the ejecta cone angles, we use a uniform distribution, f_ψ , normalized to unity in the range $\psi \in [0, \psi_0]$:

$$f_\psi(\psi) = \frac{\sin \psi}{1 - \cos \psi_0}$$

The mass distribution of the grains is uncorrelated with the velocity and is described as a power law that is normalized to the total rate of mass production in the range $m \in [m_{\min}, m_{\max}]$ (refs 12 and 18). The generalized version of equation (1) becomes

$$n(m, v, \theta, \phi; r) = \frac{M^+}{8\pi^2 R r} \frac{1 - \alpha}{m_{\max}^{1-\alpha} - m_{\min}^{1-\alpha}} m^{-(1+\alpha)} \frac{f_u(u(v)) f_\psi(\psi(v, \theta))}{v u(v)^2 \sin \theta \cos \psi(v, \theta)} \quad (2)$$

where M^+ denotes the total mass production rate that is related to N^+ as

$$N^+ = M^+ \frac{1 - \alpha}{\alpha} \frac{m_{\min}^{-\alpha} - m_{\max}^{-\alpha}}{m_{\max}^{1-\alpha} - m_{\min}^{1-\alpha}}$$

The exponent is expected^{12,30} to be in the range $0.5 \leq \alpha \leq 1$. Equation (2) gives the number of particles found at distance r from the centre of the moon in the phase space volume element $d^3v d^3r dm$.

When a grain of mass m hits the dust detector at a velocity v it produces an impact charge²⁹

$$q = cmv^\beta \quad (3)$$

The combination of equations (2) and (3) can be used to estimate the distribution of charges to be recorded by LDEX in the following manner.

Typically the LADEE spacecraft followed a nearly circular orbit around the moon with speed v_{sc} relative to the surface. The boresight of LDEX pointed in the direction of spacecraft motion (apex) so that the detector encountered dust grains of velocity $\mathbf{v}$ at a relative velocity $\mathbf{v}_{\text{sc}} - \mathbf{v}$. The number of grains ΔN with velocity in d^3v and mass in dm , that can reach the detector during time Δt , is given by the number of such grains found in a cylindrical volume spanned by the detector surface A and the relative velocity vector (Extended Data Fig. 1)

$$\Delta N = A \Delta t d^3v dm A(\omega) \cos \omega \Theta_H(\cos \omega) n(m, v, \theta, \phi; r) |\mathbf{v} - \mathbf{v}_{\text{sc}}| \quad (4)$$

where ω is the angle between the boresight and the relative velocity vector. The Heaviside function, $\Theta_H(\cos \omega)$, guarantees that we count only grains that can enter the detector. With $A(\omega)$ we account for the fact that the effective detector area of LDEX depends on the angle ω . The effective area is maximal for $\omega = 0$, dropping to zero for $\omega = 68$ degrees (ref. 22). We evaluate $\cos \omega$ in terms of the spacecraft and dust velocities, as well as the angles ϕ, θ by noting that for a circular spacecraft orbit

$$\cos \omega = \frac{v_{\text{sc}} - v \sin \theta \cos \phi}{|\mathbf{v} - \mathbf{v}_{\text{sc}}|} \quad (5)$$

Dividing (4) by Δt we obtain the differential rate $d\gamma$ of particles that impact the detector

$$d\gamma = dv v^2 d\theta d\phi \sin \theta dm A(\omega) (v_{\text{sc}} - v \sin \theta \cos \phi) \Theta_H(v_{\text{sc}} - v \sin \theta \cos \phi) n(m, v, \theta, \phi; r) \quad (6)$$

where $A(\omega)$ is expressed with equation (5) as a function of v, θ, ϕ . We re-arrange the right-hand side of (6) into a mass and a velocity distribution as

$$d\gamma = dv d\theta d\phi dm p_m(m) p(v, \theta, \phi; r, \psi_0, \mu, u_0)$$

where

$$p_m(m) = M^+ \frac{1 - \alpha}{m_{\max}^{1-\alpha} - m_{\min}^{1-\alpha}} m^{-(1+\alpha)} \Theta_H(m - m_{\min}) \Theta_H(m_{\max} - m) \quad (7)$$

and

$$p(v, \theta, \phi; r, \psi_0, \mu, u_0) = \frac{A(\omega)}{8\pi^2 R r} (v_{\text{sc}} - v \sin \theta \cos \phi) \Theta_H(v_{\text{sc}} - v \sin \theta \cos \phi) v^{\frac{f_u(u(v)) f_\psi(\psi(v, \theta))}{u(v)^2 \cos \psi(v, \theta)}}$$

We define

$$p_v(v) = \int_0^\pi d\theta \int_0^{2\pi} d\phi p(v, \theta, \phi; r, \psi_0, \mu, u_0)$$

Using equation (3) we can then $\pi \pi$ express the model prediction for the distribution of charges detected by LDEX as

$$p_q(q) = \int d\gamma \delta(q - mcv^\beta) = \int_0^\infty dm p_m(m) \int_0^\infty dv p_v(v) \delta(q - mcv^\beta) = \int_0^\infty dv \frac{p_v(v)}{cv^\beta} p_m\left(\frac{q}{cv^\beta}\right)$$

Inserting equation (7) and sorting terms gives

$$p_q(q) = \frac{M^+}{m_{\max}} \frac{1 - \alpha}{1 - \left(\frac{m_{\min}}{m_{\max}}\right)^{1-\alpha}} \frac{1}{q} \left(\frac{cm_{\max}}{q}\right)^\alpha \int_{v_{\min}(q)}^{v_{\max}(q)} dv p_v(v) v^{2\beta} \quad (8)$$

where the boundaries

$$v_{\min}(q) = \left(\frac{q}{cm_{\max}} \right)^{1/\beta}, \quad v_{\max} = \left(\frac{q}{cm_{\min}} \right)^{1/\beta}$$

follow from the normalization of the mass distribution, equation (7).

Evaluating $p_v(v)$ shows that the integral in equation (8) depends only weakly on the charge q via the boundaries. Quantitatively,

$$0.13 < \frac{\int_{v_{\min}(q)}^{v_{\max}(q)} dv p_v(v) v^{2\beta}}{\int_0^\infty dv p_v(v) v^{2\beta}} < 0.23$$

when changing q from 0.1 fC to 1,000 fC. Therefore, the distribution $p_q(q)$ is dominated by far by the power law, so that we expect to see

$$p_q(q) \propto q^{-(1+\alpha)}$$

in the data. Hence, measuring the exponent of the impact charge distribution yields the exponent of the mass distribution of the particles recorded by LDEX.

Dust production from impacts. Extended Data Fig. 3 and Extended Data Table 1 were generated assuming that the LT-averaged ejecta cloud is spherically symmetric to determine the bulk properties of the cloud and allow for direct comparison with previous studies^{12,30}. Here we address the anisotropic nature of the dust influx to the lunar surface. To this end we replace the single global dust mass production M^+ with an LT- and time (t)-dependent function of mass production per unit surface area $M^+(\text{LT}, t)$.

The mass flux of bombarding interplanetary dust particles with mass m and velocity v is a function of both the position on the lunar surface and time: $F(m, v, \text{LT}, t)$. A single dust particle striking a pure silica surface generates a large number of ejecta particles with a total mass $m^+ = mY(m, v)$, where the yield, $Y \sim m^{0.2} v^{2.5}$, is determined on the basis of laboratory experiments³¹. The mass flux of impactors is dominated by particles with characteristic mass $m_0 \approx 10^{-8}$ kg (about 100 μm in radius)³². Our detected impacts are dominated by ejecta particles generated along the ground track of the spacecraft that followed a nearly equatorial orbit. Hence, it is convenient to track the position on the lunar surface in LT, with LT = 0, 6, 12, 18 marking midnight, the dawn terminator, the sub-solar point and the dusk terminator, respectively. The mass production rate per surface area as function of LT is found by integrating the product of the interplanetary dust flux F and the yield Y around the lunar equator

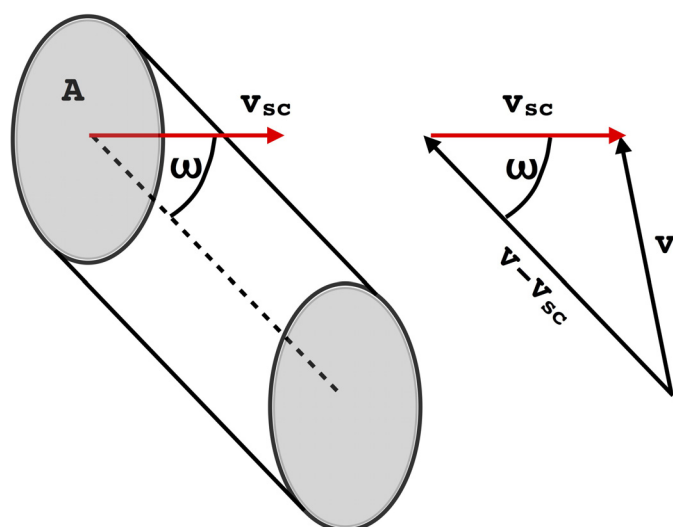
$$M^+(\text{LT}, t) = \iint F(m, v, \text{LT}, t) Y(m, v) dm dv \quad (9)$$

We evaluated equation (9) using both NASA's MEM¹⁶ and ESA's IMEM¹⁷ models, which agree well near one astronomical unit. The flux F and the predicted mass production rates $M^+(\text{LT}, t)$ are shown in Extended Data Fig. 4, and are consistent with the asymmetric dust ejecta cloud observed by LDEX. We note that the meteoroid population still remains one of the most uncertain space environment components³³.

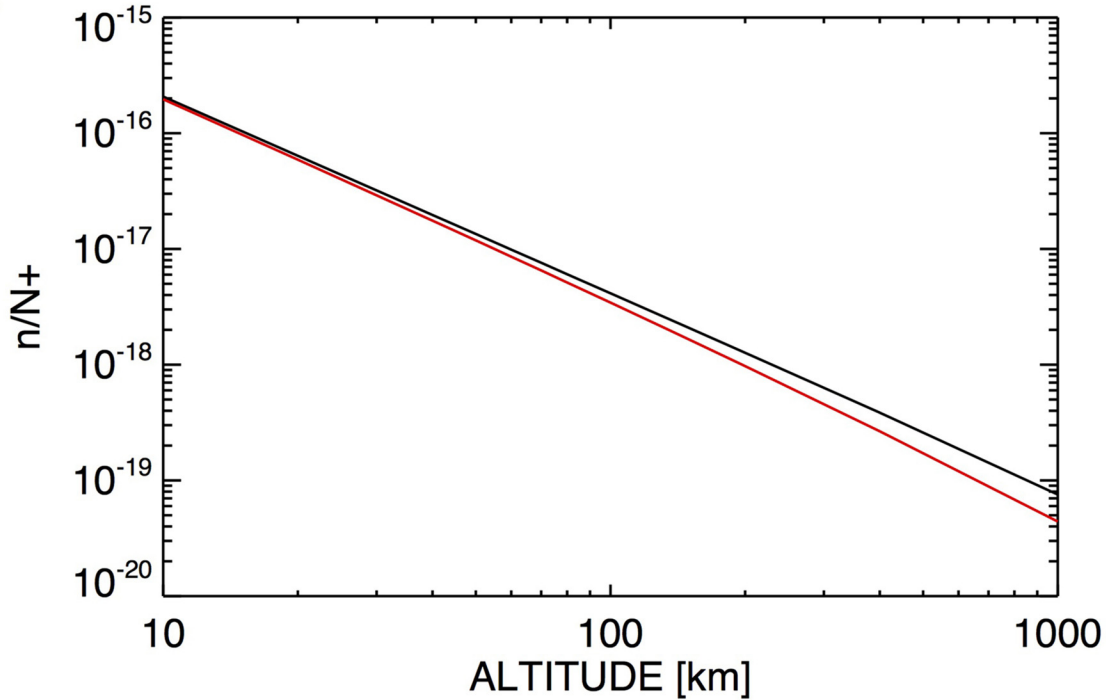
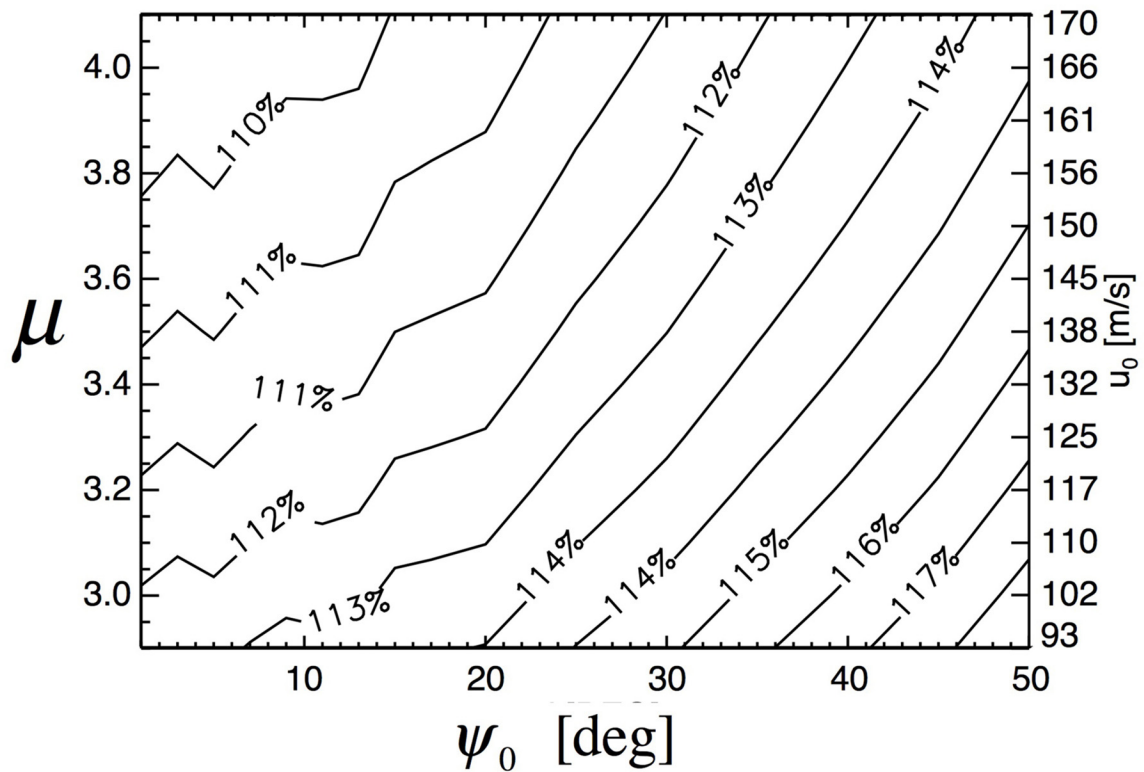
Data availability. All LDEX data are available through NASA's Planetary Data System (<http://sbn.psi.edu/pds/resource/ldex.html>).

Code availability. The code used for calculating the flux of interplanetary dust particles reaching the lunar surfaces is available upon request from NASA (<http://www.nasa.gov/offices/meo/software>).

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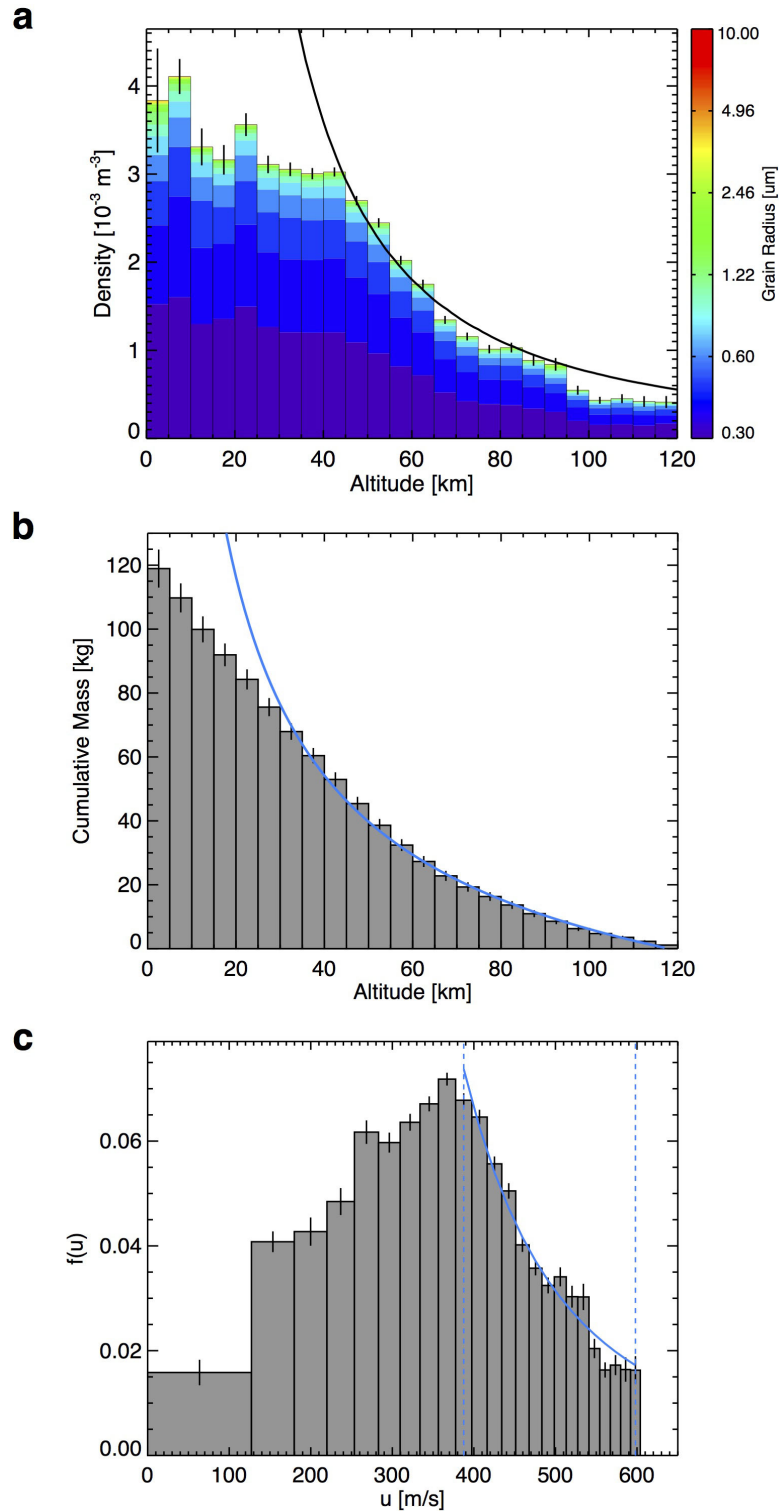


Extended Data Figure 1 | Detection geometry. A particle of velocity $\mathbf{v}$ is recorded by a detector of sensitive area A . The surface normal of the detector area points along the velocity vector of the spacecraft $\mathbf{v}_{sc}$. The particle enters the instrument with an angle ω measured between the instrument boresight and the relative velocity vector of the particle $\mathbf{v}_{sc} - \mathbf{v}$.

a**b**

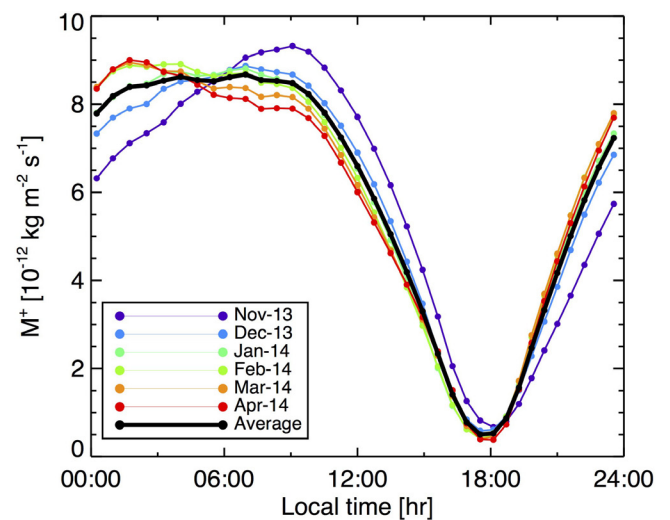
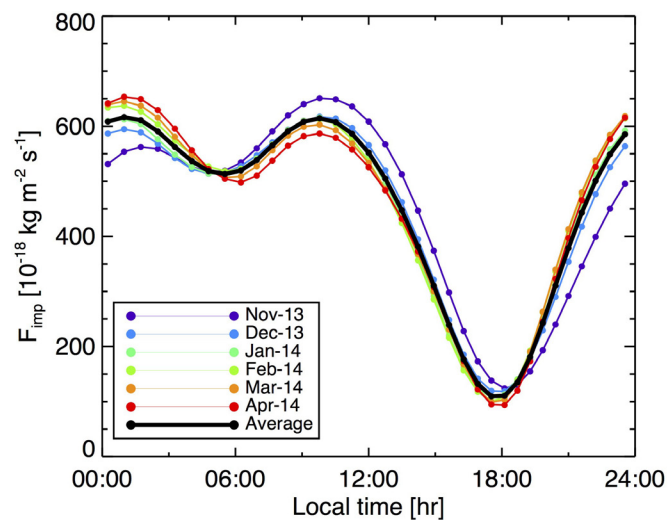
Extended Data Figure 2 | Systematic approximation error and its dependence on ejection parameters. **a**, The calculated density for a standard set of parameters listed in Extended Data Table 1 for the model ejecta cloud¹² as function of altitude (black line) normalized to the production rate N^+ . The density is recalculated using $n = \gamma/(A v_{sc})$ (red line), the approach taken in this paper to infer the dust density from the measured impact rates γ , indicating an

underestimate of $<20\%$ for altitudes below 100 km. **b**, Contour plot of the ratio of the 'true' model density over the recalculated density at the altitude $h = 50$ km, as a function of the opening cone angle of the ejecta plume ψ_0 and the exponent of the power-law initial-speed distribution μ , appropriately setting the minimum speed u_0 , while keeping the maximum speed constant at $2v_{escape}$, maintaining a constant total kinetic energy of the ejecta particles.



Extended Data Figure 3 | Comparison of observed and modelled cloud properties. **a**, The dust density $n(h)$ of the lunar ejecta cloud as function of altitude and size (colour scale). The continuous black line shows the model prediction¹² using the best-fit parameters listed in Extended Data Table 1. **b**, The cumulative dust mass in the lunar exosphere. The continuous blue line shows the ejecta model prediction (Extended Data Table 1). **c**, The initial

normalized vertical velocity distribution $f(u)$ calculated from $n(h)$ using energy conservation. The continuous line shows $f(u) \propto u^{-3.4 \pm 0.1}$ matched to the data at $u \geq 400 \text{ m s}^{-1}$ (altitude $h \approx 50 \text{ km}$). Error bars were calculated by propagating the $\sqrt{N}$ error through the various calculations, where N is the number of detected dust impacts.



Extended Data Figure 4 | Modelled flux and mass production in the lunar equatorial plane. **a**, The calculated flux of interplanetary dust particles F_{imp} reaching the lunar equatorial region as a function of LT and t (colour coded for

monthly averages). **b**, The mass production rate, equation (9), calculated using a model for the spatial and velocity distributions of interplanetary dust particles near the Earth¹⁶, consistent with the observed asymmetric dust cloud.

Extended Data Table 1 | Parameters of the theoretical ejecta cloud model¹² for the Moon

Parameter	Definition	Value
mass distribution	$N^+(\geq m) \propto m^{-\alpha}$	$\alpha = 0.91 \pm 0.003$
smallest mass*	m_{min}	$3 \cdot 10^{-16}$ kg
largest mass**	m_{max}	10^{-8} kg
speed distribution	$f_u(u) \propto u^{-\mu}$	$\mu = 3.4 \pm 0.1$
minimum speed	u_0	130 m/s
maximum speed	$u_{max} = 2 \cdot v_{escape}$	4.8 km/s
impactor speed	v_{imp}	20 km/s
ratio of ejecta/impactor kinetic energy	K_e/K_i	20%
ratio of ejecta/impactor mass	Y	1000
initial velocity maximum cone angle	ψ_0	30°

*radius $a_{min} = 0.3 \mu\text{m}$; ** $a_{max} = 100 \mu\text{m}$

These parameters form a consistent set, and are not independent of each other³⁰.