

Dusty Streaks on the Moon: Fingerprints of Multiphase Flow Instabilities

Corresponding Author: Professor Rui Ni

This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

This manuscript presents an interpretation of the distinctive dust streaks observed after the interaction between spacecraft exhaust plumes and lunar soil. The authors provide both experimental and numerical data supporting the hypothesis that these streaks result from preferential dust accumulation caused by Görtler vortices forming within the jet plume and spreading around the jet impingement region.

The topic is of significant theoretical interest and addresses an important research question. The authors' interpretation appears to be overall supported by experimental evidence, and I find no obvious technical shortcomings in either the experimental setup or the analysis. However, I have some reservations about endorsing the paper in its current form, primarily due to a general lack of clarity and logical flow in the presentation of results.

That said, I would be happy to review a revised version of the manuscript that addresses the following points.

1. The authors conduct three separate investigations:

- 1) visualizations of an impinging jet on a granular bed,
- 2) numerical simulations of a single-phase overexpanded jet, and
- 3) numerical simulations of free jets.

A more logical ordering would be 2-3-1, whereas the authors present it as 1-3-2, which feels awkward. It would be more informative to first describe the jet plume's characteristics before discussing sand deposition.

2. The results of the numerical simulations are barely utilized and are discussed in just eight lines on page 5.

3. The connection between Figures 2c and 2d is somewhat vague.

4. The key claim appears to be that the streaks result from Görtler vortices embedded in the shear layer of the impinging jet. However, this is never explicitly demonstrated. Regarding the numerical simulations, the authors state: "They provided enhanced visualization of the flow and supported the hypothesis that vortical structures originate near the nozzle exit." Seeing these visualizations would be crucial to supporting this claim.

5. In conventional terminology, Görtler vortices are typically associated with flows over concave surfaces. Here, the authors seem to be referring to centrifugal instabilities within the jet shear layer. This raises several questions: Is the nomenclature still appropriate in this context? Does the same scaling law that applies to wall-bounded flows hold here as well? Can the authors reference any previous theoretical studies on these instabilities?

6. Figure 4 is poorly explained, with key information missing. For instance, to which z do panels (c) and (f) correspond? It is unclear how the z coordinate used in panels (b) and (e) aligns with that in panels (a) and (d).

Conclusion

This paper is potentially interesting, but it suffers from major issues in terms of presentation and possibly even interpretation. I encourage the authors to address these concerns in a revised version.

Reviewer #2

(Remarks to the Author)

This is a high quality work that studies the stable streak patterns observed in various landing lunar sites combined with careful and controlled laboratory experiments, and proposes a mechanism of Gortler vortices for their formation of and for the number of streaks. The noteworthy aspects are the careful and somewhat challenging experiments and supportive numerical simulations, the discovery of a commonality in the stable streaks observed from a variety of datasets, and the semi-quantitative predictions and comparison with laboratory experiments and field data. I believe the work and the findings reported here are novel, and will be of impact to the lunar landing research and for fundamental compressible and particle laden flows research, at low atmospheric pressure conditions. The work supports most of the conclusions and the methodologies appear to be sound and of sufficiently high quality. I have not much doubt about the validity of the experimental findings. However, I have a few questions, in particular about the scalings observed. If the authors can address these the paper might send a clearer picture to readers. I also have a few minor comments about the presentation of certain sections, which the authors may provide more clarifications about.

1. During lunar landing the height of the jet presumably varies. In the experiment, the distance of the jet from the surface is held fixed. Can the authors justify how these two cases are equivalent to make comparisons? Certainly their data suggests this, but are there other reasons why the aspect of an approaching lander and a fixed jet are similar?
2. The volume of the chamber is reported to be 75 m^3 . This is presumably approx. $4 \text{ m} \times 4 \text{ m} \times 5 \text{ m}$? Could information about the dimensions of the experiment be given? And how was this chosen?
3. Authors note that the jet in the experiment does not change the conditions in the chamber. This presumably is time dependent, and if the jet continues for long duration, the pressure in the chamber would increase. Can the authors give more quantitative arguments based on the mass flux of the jet, the volume of the chamber and a time constant, how this deduction that the pressure conditions in the chamber remains nearly unchanged during the experiment?
4. Can the authors give more details on how the Gortler prediction datapoints in Fig. 3 were obtained? They seemingly agree with the $1/3$ scaling prediction.
5. A minor comment: In the equations listed, Eq. 4 seems to be a relatively straightforward expression for non-linear curvature. This equation is highlighted and numbered. Is this expression a very crucial ingredient of the paper that needs to be highlighted? By writing down the nonlinear curvature, do the authors mean that a linear approximation of curvature is not sufficient?
6. The results presented in Fig 3 and Fig 4 c & d are impressive, especially the effort put in by the authors to have collection of data that tells the big picture. It is also pretty clear that the data follows power law scalings. However, I was not able to see theoretical discussion on the origin of the two $1/3$ laws, and the $1/6$ law. Is this based on the observations in Figures? Or is this based on theory? If it is observational, why do the authors state the scaling as $1/3$ and $1/6$, instead of 0.33 and 0.166 , or it's not clear why a best fit power law exponent is not shown. If I missed some key discussion or supplemental material, the authors may kindly clarify this.
7. The blue hollow squares showing without jet impingement. Could the authors clarify what they mean by this data? Is there no surface of impingement? If so, how are the streaks observed?
8. Somewhere in the paper it is stated 4 decades in τ_e . From what I could see, it spans less than 3 decades or over 2 decades, depending on how one chooses to put it. If I misinterpreted something, the authors may clarify.

Overall, I believe this paper is quite unique in combining laboratory experiments, field data and numerical simulations, providing new insights into streaks observed during lunar landing, and adding value to many other similar ongoing research efforts. In my view, this work should be published in Nature Communications.

Reviewer #3

(Remarks to the Author)

The results presented in this work are primarily related to a jet impinging on a flat granular bed. Authors in their scaled-down laboratory experimental work have tried to maintain lunar-like conditions, e.g. pressure in the chamber. This manuscript details the ejection of granular bed particles and drawing the similarity with the lunar soil particles. The subject is interesting and worth exploring. There are many researchers who have worked in this research domain since the 1960's [Lunar explorations by USA] (e.g. (a) Stitt, L. E. (1961). Interaction of highly under-expanded jets with simulated lunar surfaces. NASA report; (b) Land, N. S., & Clark, L. V. (1965). Experimental investigation of jet impingement on surfaces of fine particles in a vacuum environment. National Aeronautics Space Administration). The main conjecture of this work is regarding similarity of streak patterns during landing on extraterrestrial bodies with no atmosphere and when the lander is closer to the surface. The article is interesting and relates streak formation with the jet pressure ratio. The streak formation corresponds to the number of pairs of counter-rotating vortices. The authors are requested to clarify the points below.

The claim regarding the estimated number of streaks appeared (i.e. ranging from 30 to 70) is interesting which authors deduced from the pictures of lunar landing across the missions. The authors have mentioned the number of streaks (n) in their experiments as a function of the jet pressure ratio. In Figure 3, why for the jet pressure ratio around 50, there are two data points for "current experiments"?

If the soil had a binder of certain sort, the ejecta would show a different pattern. How has the lunar soil been reproduced in the scaled-down experiments? Will this affect the gap between two consecutive streaks?

The gravitational force on the lunar surface would be far less than that of earth. The particle sizes considered in the experiments are 150 micrometers. Is that the reason for not conducting the experiments of jet impingement of particles on a flat granular bed in conditions with reduced gravity?

The avalanches of loose particles of granular bed from the slopes of the crater are consistently seen in the crater formation studies. The continuous jet will produce ejecta of soil particles. These particles are made available due to the avalanches. Is this avalanche phenomenon observed in the experiments?

Page no. 4; the jet pressure ratio is defined as jet exit pressure to the atmospheric pressure. Here, two pumps are used to reduce pressure inside the experimental setup for vacuum-like conditions. Hence, reference to atmospheric pressure is puzzling.

The authors give a paragraph on numerical simulations of under-expanded jets on page 5 and also refer to their article for the employed numerical scheme. However, these results are not clearly depicted (except three data points in Fig. 3) in the present manuscript.

The authors seem to have presented the work at the beginning of this year in the below forum. How different is the work presented compared to the present manuscript? [Reference: Rubio, Juan S., Neil S. Rodrigues, Yinghe Qi, Miguel X. Diaz-Lopez, Matthew T. Gorman, and Rui Ni. "On the Interaction Between a Flow Instability and Inertial Particles in Supersonic Jet Plume-Surface Interaction." In AIAA SCITECH 2025 Forum, p. 2567. 2025].

The following work may give additional insights regarding the particle ejection and cavity formation for a jet impinging on a flat granular bed.

Cuesta, Claudia Jimenez, Jack Davies, Kevin Worrall, Andrea Cammarano, and Hossein Zare-Behtash. "Plume-surface interactions: A review of experimental work." *Acta Astronautica* 226 (2025): 892-912.

Silwal, Lokesh, Vikas N. Bhargav, Daniel C. Stubbs, Brandon K. Fulone, Brian S. Thurow, David E. Scarborough, and Vrishank Raghav. "Ejecta behavior during plume-surface interactions under rarefied atmospheric conditions." *Acta Astronautica* 218 (2024): 35-46.

Guleria, Sharey Deep, and Dhiraj V. Patil. "Experimental investigations of crater formation on granular bed subjected to an air-jet impingement." *Physics of Fluids* 32, no. 5 (2020).

What are the noteworthy results?

The main conjecture of this work is regarding similarity of streak patterns during landing on extraterrestrial bodies with no atmosphere and when the lander is closer to the surface.

Will the work be of significance to the field and related fields? How does it compare to the established literature?

The work is of significance to the field of jet impingement on the granular bed. It does compare the earlier theories and concludes with a conjecture.

Does the work support the conclusions and claims, or is additional evidence needed?

Yes

Are there any flaws in the data analysis, interpretation and conclusions? Do these prohibit publication or require revision?

No

Is the methodology sound? Does the work meet the expected standards in your field?

Yes

Is there enough detail provided in the methods for the work to be reproduced?

The methods section has been quickly depicted mainly regarding the numerical simulation studies (page 5 second para; page 9 last para). I suggest the authors may publish the numerical results in specialized journals devoted to computational methods or fluid flow.

Version 1:

Reviewer comments:

Reviewer #2

(Remarks to the Author)

Authors have addressed my comments and I think this will be an important and visible contribution in Nature communications.

Reviewer #3

(Remarks to the Author)

The authors have carried out revision of the original manuscript and have answered all comments.

Open Access This Peer Review File is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made.

In cases where reviewers are anonymous, credit should be given to 'Anonymous Referee' and the source.

The images or other third party material in this Peer Review File are included in the article's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder.

To view a copy of this license, visit <https://creativecommons.org/licenses/by/4.0/>

Notes on revision made to manuscript Paper NCOMMS-24-80339

The authors extend their sincere gratitude to the editor and reviewers for their valuable feedback and constructive suggestions, which have significantly enhanced the quality of this manuscript. We have carefully revised the manuscript in accordance with all comments received. Our detailed responses follow below. For ease of review, all substantial modifications in the revised manuscript are highlighted in [blue](#).

Response to the reviewers

Reviewer 1

This manuscript presents an interpretation of the distinctive dust streaks observed after the interaction between spacecraft exhaust plumes and lunar soil. The authors provide both experimental and numerical data supporting the hypothesis that these streaks result from preferential dust accumulation caused by Görtler vortices forming within the jet plume and spreading around the jet impingement region.

The topic is of significant theoretical interest and addresses an important research question. The authors' interpretation appears to be overall supported by experimental evidence, and I find no obvious technical shortcomings in either the experimental setup or the analysis. However, I have some reservations about endorsing the paper in its current form, primarily due to a general lack of clarity and logical flow in the presentation of results.

That said, I would be happy to review a revised version of the manuscript that addresses the following points.

Reply: We would like to thank the reviewer for the comments and suggestions. We have made changes of the presentation and logical flow to improve the overall clarity of the paper. The detailed replies can be found below.

Reviewer Comment 1.1 — The authors conduct three separate investigations:

- 1) visualizations of an impinging jet on a granular bed,
- 2) numerical simulations of a single-phase overexpanded jet, and
- 3) numerical simulations of free jets.

A more logical ordering would be 2-3-1, whereas the authors present it as 1-3-2, which feels awkward. It would be more informative to first describe the jet plume's characteristics before discussing sand deposition.

Reply: We apologize for the confusion. We would like to clarify the intention of our chosen order. The reason that the multiphase experiments were presented first is to connect to the actual landing footage where the dusty streaks were observed. So we chose (1) first to show that the same pattern can be reproduced in a low-pressure environment at a much smaller scale. Then, we showed that the

pattern can be explained once we look into the flow physics of the single-phase underexpanded jet. It is important to emphasize that (2) is from experimental results, in which we conducted measurements of the single-phase underexpanded jet impinging on a flat plate at the same condition to focus on the jet dynamics. The last one [part (3)] is indeed the simulation result, but it was only added in the end to confirm the finding. It was not meant to be the main point since the simulation was computed for a free jet instead of an impinging jet. We decided to keep the order as is but added more details on the numerics in the Supplementary Material as the reviewer suggested.

Reviewer Comment 1.2 — The results of the numerical simulations are barely utilized and are discussed in just eight lines on page 5.

Reply: We have added more numerical details in the Supplementary Material. Here we summarize the main points mentioned.

- **Governing Equations:** The viscous compressible Navier–Stokes equations are solved using a high-order, energy-stable finite difference scheme.
- **Numerical Methods:**
 - Fourth-order finite difference schemes with summation-by-parts (SBP) property.
 - Skew-symmetric splitting for kinetic energy preservation.
 - Artificial dissipation using localized artificial diffusivity for shock capturing.
 - Non-reflecting boundary conditions and immersed boundary methods for solid surfaces.
- **Temporal Integration:** Fourth-order Runge-Kutta method with CFL restrictions for stability.
- **Simulation Configurations:**
 - Two nozzle configurations: a sonic nozzle ($M_e = 1$) and a supersonic nozzle ($M_e = 5.3$).
 - Computational grid resolutions tailored to capture flow features accurately.
 - Simulations performed on a high-performance computing cluster.
- **Key Analysis:**
 - Streamwise vortex structures analyzed through density and vorticity contours.
 - Vortex patterns fitted using sinusoidal functions to quantify streak structures.

We hope these additions provide greater clarity on the numerical approach used in our study.

Reviewer Comment 1.3 — The connection between Figures 2c and 2d is somewhat vague.

Reply: We agree with the reviewer that the actual image and the illustration is a bit vague, but we cannot find a better way to connect them since the experimental image near the surface is often contaminated with high concentration of dust particles, making it difficult to visualize the streak structures from a steep angle. As a result, we intend to keep the figure as is since it is the best that we can do for now.

Reviewer Comment 1.4 — The key claim appears to be that the streaks result from Görtler vortices embedded in the shear layer of the impinging jet. However, this is never explicitly demonstrated. Regarding the numerical simulations, the authors state: “They provided enhanced visualization of the flow and supported the hypothesis that vortical structures originate near the nozzle exit.” Seeing these visualizations would be crucial to supporting this claim.

Reply:

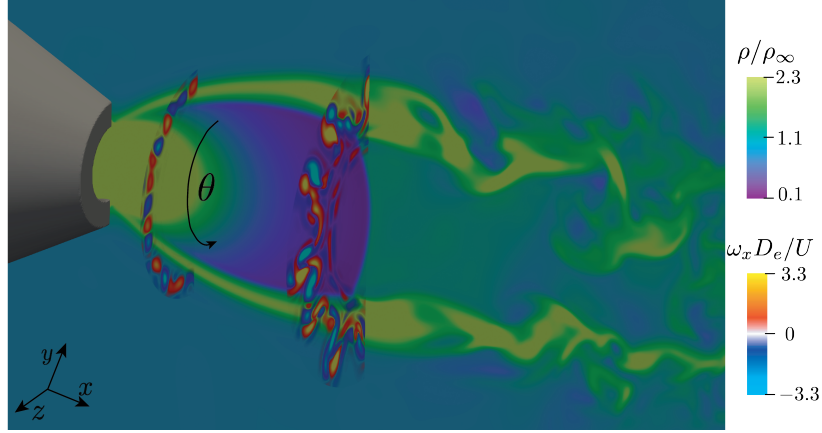


Figure 1: Instantaneous snapshot of the computed gas jet at $\eta_e = 15.4$, showing contours of gas density (on $x - z$ plane) (blue/green) and streamwise-component (on $y - z$ plane at $x/D_e = 1.25$) of vorticity (red/blue).

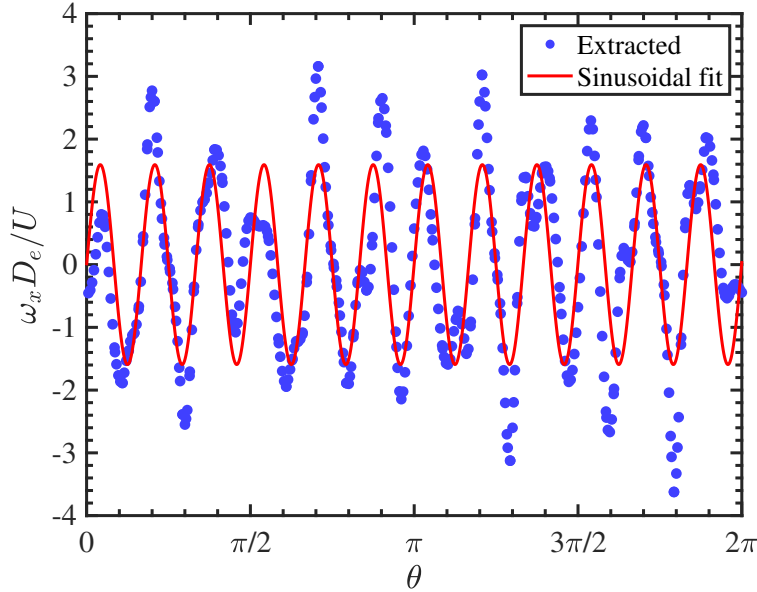


Figure 2: Unwrapped streamwise component of vorticity at $x/D_e = 1.25D_e$, and radius $R_\omega = 1.37D_e$ fitted by $A\sin(n\theta)$ with $n \approx 12$ and $A \approx 1.65$ for the sonic nozzle with $\eta_e = 15.8$.

We thank the reviewer for this comment. We have added new supplementary material with two

accompanying figures, which are also shown here. The simulations were conducted until the system reached a steady state at $tU/D_e = 185$, where U is the velocity at the nozzle exit. The number of counter-rotating vortex pairs, or streaks, was determined by visualizing the streamwise vorticity component in cross-sectional views of the jet near the nozzle exit, as depicted in Figure 1, highlighting pairs of clockwise and counterclockwise vortex structures. A one-dimensional plot was then generated by selecting a circular radius ($R_\omega = 1.37D_e$) that intersects the vortex centers. This circular path was transformed into an angular plot ranging from 0° to 360° . The vortex pairs were counted by fitting a sinusoidal curve to the data, which revealed the number of distinct streaks, n (see Figure 2).

Reviewer Comment 1.5 — In conventional terminology, Görtler vortices are typically associated with flows over concave surfaces. Here, the authors seem to be referring to centrifugal instabilities within the jet shear layer. This raises several questions: Is the nomenclature still appropriate in this context? Does the same scaling law that applies to wall-bounded flows hold here as well? Can the authors reference any previous theoretical studies on these instabilities?

Reply: Reviewer raised an excellent point. The shear flow over a concave surface is subject to a centrifugal instability whose inviscid mechanism was first given by Rayleigh (1916). The Görtler instability is just one type of the Rayleigh circulation criterion. Other types include Taylor and Dean. Depending on whether they are closed (Taylor) or open (Görtler and Dean) systems and whether they are parallel (Taylor and Dean) or boundary-layer (Görtler) flows. The distinction between these instabilities has not always been clear and hence, one is likely to see the name of Taylor associated with all three of these types of flows. However, the presentation that follows will show that the spatial, nonparallel, open-flow characteristics of the Görtler problem make it quite unique. It shares neither the complex and interesting bifurcations of the Taylor problem (Coles 1965) nor the mathematical simplicity of the Dean problem (Drazin & Reed 1981). The name Görtler instability is therefore reserved to the growth of the vortices in an open, nonparallel system, which is exactly the flow of interest in this paper. It is less on the nature of the boundary condition being solid surface. So, we believe that the name used here is appropriate.

Reviewer Comment 1.6 — Figure 4 is poorly explained, with key information missing. For instance, to which z do panels (c) and (f) correspond? It is unclear how the z coordinate used in panels (b) and (e) aligns with that in panels (a) and (d).

Reply: We thank the reviewer for catching this error. We indeed made a mistake of using z differently. In panel (a) and (d), z reaches zero at the surface of the substrate whereas the zero point was at the nozzle exit for panel (b) and (e). We have now changed the x -axis in figures (b) and (e) starting from the nozzle exit. Regarding panels (c) and (f), the data shows the key variables with the vertical bars corresponding to the standard deviation in the z direction. This information is reflected in the last sentence of the caption in Figure 4.

Reviewer 2

This is a high quality work that studies the stable streak patterns observed in various landing lunar sites combined with careful and controlled laboratory experiments, and proposes a mechanism of Gortler vortices for their formation of and for the number of streaks. The noteworthy aspects are the careful and somewhat challenging experiments and supportive numerical simulations, the discovery of a commonality in the stable streaks observed from a variety of datasets, and the semi-quantitative predictions and comparison with laboratory experiments and field data. I believe the work and the findings reported here are novel, and will be of impact to the lunar landing research and for fundamental compressible and particle laden flows research, at low atmospheric pressure conditions. The work supports most of the conclusions and the methodologies appear to be sound and of sufficiently high quality. I have not much doubt about the validity of the experimental findings. However, I have a few questions, in particular about the scalings observed. If the authors can address these the paper might send a clearer picture to readers. I also have a few minor comments about the presentation of certain sections, which the authors may provide more clarifications about.

Reply: We would like to thank the reviewer for support and great insights. We have addressed the questions and comments below in detail.

Reviewer Comment 2.1 — During lunar landing the height of the jet presumably varies. In the experiment, the distance of the jet from the surface is held fixed. Can the authors justify how these two cases are equivalent to make comparisons? Certainly their data suggests this, but are there other reasons why the aspect of an approaching lander and a fixed jet are similar?

Reply: The reviewer is right. In most cases, lunar landing comes with a descent rate. But in the Apollo landings, it has happened that, because of the downrange error noted during the initial descent, the lander was taking the crew to a boulder-strewn crater. Armstrong took over manual control. He halted the descent, hovered, and then flew sideways in search of a smoother landing area, during which the streaks start to emerge. However, that was only one data point, and the rest of the data points, especially the uncrewed landers, did not have the hovering phase when the distance between jet and surface was maintained constant.

Nevertheless, for approaching landers, the time to develop streaks is related to the time it takes for vortical structures impinging on the surface and entrain particles, which can be roughly estimated by using lander height divided by the jet velocity. Since the jet speed is on the order of 1000 m/s, and the lander height is on the order of 10-100 meters, the time is roughly on the order of 10-100 ms. At the same time, the descending rate ranges between 1 to 15 feet per second based on the Apollo missions' log, which is about 2 orders of magnitude slower than the jet velocity. Over 100 ms that takes the jet from the nozzle exit to the ground, the lander descended only about 0.45 m even at the highest descent velocity, which is much smaller than the distance between the lander and the ground. So, the small descent velocity in comparison with the high-speed jet velocity renders an approaching lander not significantly different from to a stationary one.

Reviewer Comment 2.2 — The volume of the chamber is reported to be 75 m³. This is

presumably approx. 4 m x 4 m x 5 m?? Could information about the dimensions of the experiment be given? And how was this chosen?

Reply: The chamber is a cylindrical chamber with a diameter of 4.57 m and a height of 4.57 m, which results in a volume of 75 m³. The dimensions of the soil bin are listed on Figure 2. The vacuum chamber was chosen for (a) its large size to mitigate the pressure rise when gas is injected into the chamber (2) its capability of lowering the ambient pressure to 2.67 Pa, and (3) being able to handle soil (dirty conditions).

Reviewer Comment 2.3 — Authors note that the jet in the experiment does not change the conditions in the chamber. This presumably is time dependent, and if the jet continues for long duration, the pressure in the chamber would increase. Can the authors give more quantitative arguments based on the mass flux of the jet, the volume of the chamber and a time constant, how this deduction that the pressure conditions in the chamber remains nearly unchanged during the experiment?

Reply: We directly monitored the chamber pressure over time. To show its influence to key quantities, in Figure 3, the jet pressure ratio η_e and the Reynolds number Re' are plotted as a function of time. Although both rise from $t = 0$ s to $t = 0.05$ s, they quickly plateaued. This is also evident in the unchanging morphology of the jets in the inset. Since the streaks developed as η_e and Re' were in the plateau region, we concluded that the flow condition and background pressure remains close to a constant for the dynamics of interest in this paper.

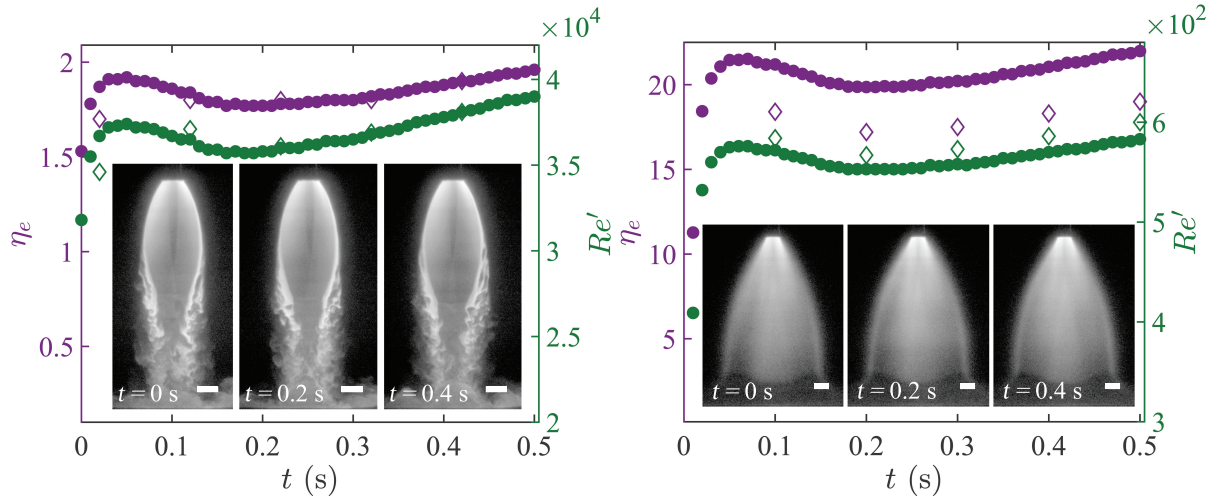


Figure 3: Evolution of the jet pressure ratio η_e and Reynolds number Re' for two different jet pressure ratios. The solid symbols represent the measured η_e (green) and Re' (purple) when the jet impinges on a bed of sand. Hollow symbols represent the extracted η_e (green) and Re' (purple) for the single-phase data when the jet impinges on a flat plate. The scale bar is 1.4 cm.

Reviewer Comment 2.4 — Can the authors give more details on how the Gortler prediction datapoints in Fig. 3 were obtained? They seemingly agree with the 1/3 scaling prediction.

Reply: The steps of acquiring the Görtler prediction are listed below. They were discussed in detail in the manuscript, but here we added more details related to which step is from our measurements versus the part from the theoretical prediction, hopefully adding clarification to the procedure.

- Measure the dimensionless radius of curvature $\mathcal{R}$ and the compressed shear layer thickness δ (from direct experimental results).
- Calculate the Görtler number G , which depends on $\mathcal{R}$ and δ .
- Use previous normal-mode solution (Floryan & Saric 1982) to determine the maximum instability growth rate β for a given Görtler number.
- Compute the wavelength λ using the relation:

$$\lambda = \frac{2\pi\delta}{\beta}$$

- Obtain the number of counter-rotating vortices (streaks) using:

$$n = \frac{\pi D}{\lambda}$$

Reviewer Comment 2.5 — A minor comment: In the equations listed, Eq. 4 seems to be a relatively straightforward expression for non-linear curvature. This equation is highlighted and numbered. Is this expression a very crucial ingredient of the paper that needs to be highlighted? By writing down the nonlinear curvature, do the authors mean that a linear approximation of curvature is not sufficient?

Reply: No, this equation is not that important and is just stating the way it was computed from the experimental data. We have now merged it with the rest of the text without highlighting it.

Reviewer Comment 2.6 — The results presented in Fig 3 and Fig 4 c & d are impressive, especially the effort put in by the authors to have collection of data that tells the big picture. It is also pretty clear that the data follows power law scalings. However, I was not able to see theoretical discussion on the origin of the two 1/3 laws, and the 1/6 law. Is this based on the observations in Figures? Or is this based on theory? If it is observational, why do the authors state the scaling as 1/3 and 1/6, instead of 0.33 and 0.166, or it's not clear why a best fit power law exponent is not shown. If I missed some key discussion or supplemental material, the authors may kindly clarify this.

Reply: The scalings shown in the article in Figures 4(c) and 4(f) were based on the measured data. For δ vs. η_e , the fitted power-law exponent is 0.167. For $\mathcal{R}$ vs. η_e , the fitted power-law exponent is 0.325. These two numbers are very close to 1/6 and 1/3. So, we decided to keep them in the figure for illustration but clarify that they are fits to our data.

In particular, we revised the paper on the second paragraph of Page 7 as:

"The same procedure was repeated for another dataset of impinging jets to extract $\mathcal{R}$ at a different $M_e = 2.6$ and $\eta_e = 3.4 - 18.5$, which agrees with our data and follows a similar power law of $\mathcal{R} \sim \eta_e^{1/3}$ with a fitted exponent of approximately 0.33 (close to 1/3)"

Also, in the third paragraph of Page 7 we added that:

"the compressed shear layer thickness for current experiments and data from Inman (2009) follow a power-law scaling of $\delta \sim \eta_e^{1/6}$ with a fitted exponent of approximately 0.167 (close to 1/6)"

Reviewer Comment 2.7 — The blue hollow squares showing without jet impingement. Could the authors clarify what they mean by this data? Is there no surface of impingement? If so, how are the streaks observed?

Reply:

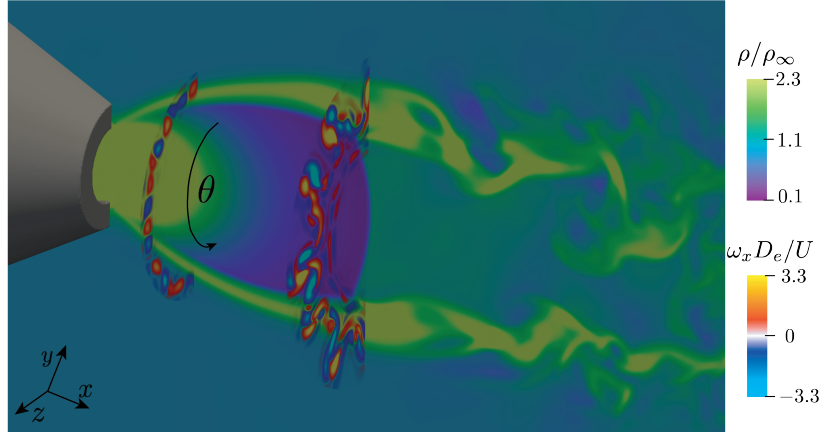


Figure 4: Instantaneous snapshot of the sonic nozzle with $\eta_e = 15.8$ showing contours of gas density (on x-z plane) (blue/green) and streamwise-component (on y-z plane at $x/D_e = 1.25D_e$) of vorticity (red/blue).

We thank the reviewer for pointing out this confusion. The reviewer is correct. The blue hollow squares in Figure 3 in the manuscript are numerical simulations of a free jet without impingement, similar to the numerical simulations performed here, which are shown as green hollow squares in the same figure. The parameter n indicates the number of counter-rotating vortex pairs inside the compressed shear layer of the free jet. We hypothesized that these counter-rotating pairs fan out as the jet impinges on the surface, entraining sand particles and resulting in ejecta streaks. We have added more details in the Supplementary Material regarding the numerical simulations. More specifically, Figures 1 and 2 in the Supplementary Material and the discussion following these figures explains how the parameter n was extracted from the simulations.

Here, we summarize some key aspects. The simulations were conducted until the system reached a steady state at $tU/D_e = 185$, where U is the velocity at the nozzle exit. The number of counter-rotating vortex pairs, or streaks, was determined by visualizing the streamwise vorticity component in cross-sectional views of the jet near the nozzle exit, as depicted in Figure 4, highlighting pairs of clockwise and counterclockwise vortex structures. A one-dimensional plot was then generated by selecting a circular radius ($R_w = 1.37D_e$) that intersects the vortex centers. This circular path was transformed into an angular plot ranging from 0° to 360° . The vortex pairs were counted by fitting a sinusoidal curve to the data, which revealed the number of distinct streaks, n (see Supplementary Material, Figure 5).

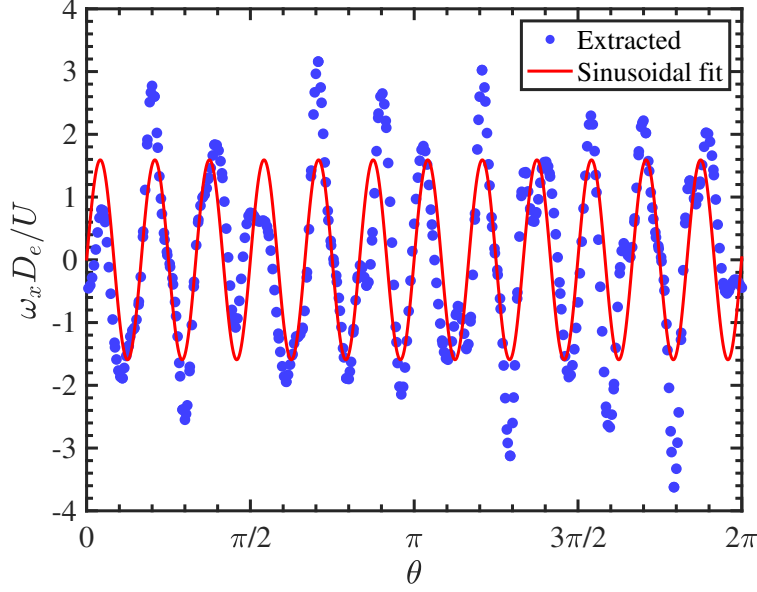


Figure 5: Unwrapped streamwise component of vorticity at $x/D_e = 1.25D_e$, and radius $R_\omega = 1.37D_e$ fitted by $A\sin(n\theta)$ with $n \approx 12$ and $A \approx 1.65$ for the sonic nozzle with $\eta_e = 15.8$.

Reviewer Comment 2.8 — Somewhere in the paper it is stated 4 decades in η_e . From what I could see, it spans less than 3 decades or over 2 decades, depending on how one chooses to put it. If I misinterpreted something, the authors may clarify.

Reply: We thank the reviewer for catching this mistake. The reviewer is correct that the data shown in Figures 4(c) and 4(f) encompass over two decades and not four as we originally stated. This change is now reflected in the article.

Overall, I believe this paper is quite unique in combining laboratory experiments, field data and numerical simulations, providing new insights into streaks observed during lunar landing, and adding value to many other similar ongoing research efforts. In my view, this work should be published in Nature Communications.

Reply: We really appreciate the reviewer for the support again.

Reviewer 3

The results presented in this work are primarily related to a jet impinging on a flat granular bed. Authors in their scaled-down laboratory experimental work have tried to maintain lunar-like conditions, e.g. pressure in the chamber. This manuscript details the ejection of granular bed particles and drawing the similarity with the lunar soil particles. The subject is interesting and worth exploring. There are many researchers who have worked in this research domain since the 1960's [Lunar explorations by USA] (e.g. (a) Stitt, L. E. (1961). Interaction of highly under-expanded jets with simulated lunar surfaces. NASA report; (b) Land, N. S., & Clark, L. V. (1965). Experimental investigation of jet impingement on surfaces of fine particles in a vacuum environment. National Aeronautics Space Administration). The main conjecture of this work is regarding similarity of streak patterns during landing on extraterrestrial bodies with no atmosphere and when the lander is closer to the surface. The article is interesting and relates streak formation with the jet pressure ratio. The streak formation corresponds to the number of pairs of counter-rotating vortices. The authors are requested to clarify the points below.

Reply: We sincerely thank the reviewer for the support and pointing out the relevant research that has been conducted in early 1960s. We are aware of these works and they inspired this research. In fact, both works reported the observation of the ejecta streak patterns. However, they did not study the physical mechanisms of these streaks, which is the focus of our study. Nevertheless, their important contribution has been acknowledged at several places throughout the entire paper. In particular, we emphasized in the introduction that

“These streaks have also been observed in terrestrial experiments conducted in preparation for the lunar landings, including those from the Apollo era [12,13,14], as well as in more recent studies motivated by renewed interest in space exploration [15,16].”

Here, we have also included the work of Conner and Land (1967) [14], which also provided evidence of the ejecta streaks.

Reviewer Comment 3.1 — The claim regarding the estimated number of streaks appeared (i.e. ranging from 30 to 70) is interesting which authors deduced from the pictures of lunar landing across the missions. The authors have mentioned the number of streaks (n) in their experiments as a function of the jet pressure ratio. In Figure 3, why for the jet pressure ratio around 50, there are two data points for “current experiments”?

Reply: We thank the reviewer for pointing the two data points at $\eta_e \sim 50$ that are close to each other. Both data points were conducted under the same pressure conditions but different separation between the jet nozzle and the granular surface (z). More specifically, one of the data points is at $\eta_e = 46.9$ and nozzle height normalized by the nozzle diameter (D_e), i.e. $z/D_e = 13$, and the other data point was conducted at $\eta_e = 48$ and $z/D_e = 10$. The resulting n is 42 and 40, respectively.

Reviewer Comment 3.2 — If the soil had a binder of certain sort, the ejecta would show a different pattern. How has the lunar soil been reproduced in the scaled-down experiments? Will this affect the gap between two consecutive streaks?

Reply: The soil used in our experiments consists of monodispersed sand particles sieved to approximately 150 μm , a size selected based on previously reported lunar regolith compositions. While we acknowledge that these particles are not identical to actual lunar soil—and that lunar soil composition varies across different landing sites—the consistent observation of streaks across locations suggests that the phenomenon is not highly sensitive to the exact soil composition. Ultimately, the formation of streaks requires only a sufficient quantity of loose surface particles that can be entrained by gas flow. Although the geomechanical properties of the bulk soil are strongly influenced by the presence of binders, these properties may play a limited role in the development of streak patterns.

Reviewer Comment 3.3 — The gravitational force on the lunar surface would be far less than that of earth. The particle sizes considered in the experiments are 150 micrometers. Is that the reason for not conducting the experiments of jet impingement of particles on a flat granular bed in conditions with reduced gravity?

Reply: We did not perform the experiments under reduced gravity conditions primarily due to the prohibitive cost. However, we believe gravity does not play a dominant role in controlling the formation of the streak patterns. The observed concentration variations between streaks and surrounding regions are primarily azimuthal rather than vertical, suggesting that gravity is unlikely to dictate the streak wavelength.

Additionally, our hypothesis is that the vortices responsible for the streak formation originate in the free jet prior to impingement and are subsequently imprinted onto the granular surface. If true, this would imply that factors such as particle type and gravity have minimal influence on the pattern formation. This hypothesis is further supported by our numerical simulations, which reproduced the streaking behavior under idealized conditions.

That being said, under reduced gravity, it is still possible that larger particles become more easily entrained in the flow, potentially increasing the vertical extent or thickness of the pattern. This is a topic worth exploring in future work if resources allow.

Reviewer Comment 3.4 — The avalanches of loose particles of granular bed from the slopes of the crater are consistently seen in the crater formation studies. The continuous jet will produce ejecta of soil particles. These particles are made available due to the avalanches. Is this avalanche phenomenon observed in the experiments?

Reply: The reviewer is correct. We did observe avalanches of loose particles as the slopes grew steeper over time. However, obvious avalanches were often observed in the late stages where the crater is deep. The streaks often appear early in the process when the crater is rather shallow.

Reviewer Comment 3.5 — Page no. 4; the jet pressure ratio is defined as jet exit pressure to the atmospheric pressure. Here, two pumps are used to reduce pressure inside the experimental setup for vacuum-like conditions. Hence, reference to atmospheric pressure is puzzling.

Reply: We apologize for the confusion. Now, for places where we referred to the ambient pressure in the vacuum chamber, we replace “atmospheric pressure” with “ambient pressure.” But since the lunar atmospheric pressure is still correct, we kept them as they were.

Reviewer Comment 3.6 — The authors give a paragraph on numerical simulations of under-expanded jets on page 5 and also refer to their article for the employed numerical scheme. However, these results are not clearly depicted (except three data points in Fig. 3) in the present manuscript.

Reply: We have added more numerical details in the Supplementary Material. Here we summarize the main points mentioned.

- **Governing Equations:** The viscous compressible Navier–Stokes equations are solved using a high-order, energy-stable finite difference scheme.
- **Numerical Methods:**
 - Fourth-order finite difference schemes with summation-by-parts (SBP) property.
 - Skew-symmetric splitting for kinetic energy preservation.
 - Artificial dissipation using localized artificial diffusivity for shock capturing.
 - Non-reflecting boundary conditions and immersed boundary methods for solid surfaces.
- **Temporal Integration:** Fourth-order Runge-Kutta method with CFL restrictions for stability.
- **Simulation Configurations:**
 - Two nozzle configurations: a sonic nozzle ($M_e = 1$) and a supersonic nozzle ($M_e = 5.3$).
 - Computational grid resolutions tailored to capture flow features accurately.
 - Simulations performed on a high-performance computing cluster.
- **Key Analysis:**
 - Streamwise vortex structures analyzed through density and vorticity contours.
 - Vortex patterns fitted using sinusoidal functions to quantify streak structures.

We hope these additions provide greater clarity on the numerical approach used in our study.

Reviewer Comment 3.7 — The authors seem to have presented the work at the beginning of this year in the below forum. How different is the work presented compared to the present manuscript? [Reference: Rubio, Juan S., Neil S. Rodrigues, Yinghe Qi, Miguel X. Diaz-Lopez, Matthew T. Gorman, and Rui Ni. "On the Interaction Between a Flow Instability and Inertial Particles in Supersonic Jet Plume-Surface Interaction." In AIAA SCITECH 2025 Forum, p. 2567. 2025].

Reply: We thank the reviewer for this question. This conference proceeding showcased the preliminary result of this work without extensive effort in modeling and understanding the streaks or the simulation results to confirm that the pattern emerged early on near the jet shear layer.

Reviewer Comment 3.8 — The following work may give additional insights regarding the particle ejection and cavity formation for a jet impinging on a flat granular bed.

Cuesta, Claudia Jimenez, Jack Davies, Kevin Worrall, Andrea Cammarano, and Hossein Zare-Behtash. "Plume-surface interactions: A review of experimental work." *Acta Astronautica* 226

(2025): 892-912.

Silwal, Lokesh, Vikas N. Bhargav, Daniel C. Stubbs, Brandon K. Fulone, Brian S. Thurow, David E. Scarborough, and Vrishank Raghav. "Ejecta behavior during plume-surface interactions under rarefied atmospheric conditions." *Acta Astronautica* 218 (2024): 35-46.

Guleria, Sharey Deep, and Dhiraj V. Patil. "Experimental investigations of crater formation on granular bed subjected to an air-jet impingement." *Physics of Fluids* 32, no. 5 (2020).

Reply: We thank the reviewer for bringing these three articles to our attention. The articles (Cuesta et al. 2025) and (Guleria et al 2020) have been cited in the last paragraph of Page 2 to support the use of a half-window for visualization of the crater. The articles (Silwal et al. 2024) and (Stubbs et al. 2025) have been cited in the second paragraph of Page 4 to showcase their visualizations of ejecta streaks in support of our observations.