

Grand Canyons on the Moon

Corresponding Author: Dr David Kring

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)

Referee report for "Grand Canyons of the Moon" by Kring et al.

The manuscript is well written. Schrodinger is a well-studied lunar basin, and as such the manuscript expands on a wide body of literature. The actual new work presented in this manuscript is somewhat limited, but I think it would be an interesting addition given the implications for Artemis astronauts' exploration of the Moon. I suggest publication, pending some minor improvements listed below.

In 33: The manuscript builds on a large body of work regarding Schrodinger. It would be good to capture uncertainties, when possible. For instance, Schrodinger age is reported following an abstract (ref 24) and quoted with two decimal digits. It should be clear that the quoted age uncertainties are not realistic, and furthermore they are based on a chronology model that has been shown to be problematic. For comparison, a close inspection at Figure 4 in Morbidelli et al EPSC 2012 shows that for $N1 \sim 1e-2$ (Schrodinger), the age uncertainty can be up to ~ 300 Myr. A more recent model, Marchi et al Nat Geo 2021, shows a similar age spread in their Figure 1. See also Nesvorny et al ApJ 2022 (their Figure 2). I will get back to this point later.

Figure 3, b: One has to wonder if the marked circles are truly impact craters. With low ballistic angles (In 142), one may expect the craters to be non circular, and the fact that they are so closely packed seems unlikely to me to be individual impacts. In this regard, I wonder if the semi-circular appearance is instead due to interaction of the scouring and slumping of the surface due to high-velocity ejecta streams. This is not a critical point, but the manuscript presents quite a bit of discussion considering the properties of these presumed craters and their impactors, while it might be these features were excavated in completely different ways.

In 138: The comment about the distributed impact zone is interesting. The argument is a bit qualitative here, and I wish the authors had included an iSALE simulation (3D) to show this. If such a simulation were available, it would make a great addition to the paper.

In 95-198: See previous comment on Schrodinger basin age. Further, there has been a great deal of work regarding the early lunar impact flux, and quoting NRC 2007 is outdated. Both sample analysis (see refs in Bottke and Norman 2017) and models (Nesvorny et al 2022; 2023) show that it is very unlikely there was a late impact spike. Still, the earliest lunar chronology is a key aspect of the Artemis' science goals, and the manuscript would benefit from a more updated discussion. In general, the NRC report is presented as a justification for this work (In 21-23), but this is a stand-alone research paper that should present interesting science regardless of the NRC goals, so I suggest rephrasing such language.

Simone Marchi
Southwest Research Institute
Boulder CO, USA

Reviewer #2

(Remarks to the Author)

I have read and completed my review of "Grand Canyons on the Moon," a manuscript submitted to Nature Communications for publication. I find the article straightforward and easy to digest, with important implications for the upcoming Artemis missions, as noted in the text. The work describes the secondary craters comprising two impressive canyons associated with Schrodinger Basin, Vallis Schrodinger and Vallis Planck. Using the secondary crater chains which presumably caused these two canyons, the authors calculate the energy required for their excavation. There are several comparisons between these two lunar canyons and the Grand Canyon on Earth, but these are primarily qualitative since the Grand Canyon formed via a very different process. However, the comparisons made in the manuscript are useful to give readers context on what is commonly intangible for most people.

My concerns are listed below, categorized into major and minor revisions for the authors.

Major Revisions

- Lines 124-126: The authors state that the larger secondary crater diameters in Vallis Schrodinger imply that they formed from clusters of fragments rather than larger intact fragments, based on scaling laws. However, this canyon also falls completely within Schrodinger's continuous ejecta blanket. Is this conclusion robust? Do the scaling laws hold for impact effects that close to the point of contact?
- Lines 143-144: How is this energy calculated (1.68×10^{20} J)? Relatedly, what is the difference between this calculation and the one for line 147 (3.39×10^{20} J). I am guessing the larger number reflects if there was a continuous line of identifiable secondary craters for the length of Vallis Schrodinger? The comparison is not clear.
- Lines 156-159: The authors mention a local slope in the vicinity of Schrodinger Basin while discussing the asymmetry of the ejecta blanket from the north to the south. This is an interesting idea, were any calculations done to determine if this slope contributes to the asymmetry? Could the upward slope to the northwest notably impede ejecta deposition?

Minor Revisions:

- Lines 90-92: Change sentence to "Vallis Planck does not show continuous secondary cratering everywhere and appears to be modified by the collapse of canyon walls." For more easy reading (change in bold).
- Line 102: Please reference the Methods section here, as it is currently unclear how these numbers are calculated.
- Lines 150-151: Please put references for the different comparisons in the main text
- Line 165: I believe the reference should go at the end of the sentence.
- Lines 180-181: Please be more explicit about the "two greatest uncertainties," I presume that this refers to the presence of the Schrodinger ejecta blanket overlying SPA material, and possibly if any ejecta from Amundsen-Ganswindt Basin will also contaminate a possible SPA collection? I find this very unclear, however.
- Line 201: Change sentence to "...so a cross-section of the Moon to a depth of ~100 km may be assessable, albeit dismembered." (change in bold)
- Line 204: Change sentence to "Excavated SPA material and any primordial crust can be used to test the lunar magma ocean hypothesis for planetary differentiation and the giant impact hypothesis for the origin of the Earth-Moon system, among many other objectives." (change in bold)
- Supplementary Figures 1 and 2: These would be more informative if there were 2 panels per figure, one with the annotations and one without. It is hard to verify the author's interpretation of the linear features without a "clean" version to review.
- Supplementary Figures 1-4, Figures 2-3: Please add N/E/S/W annotation to the map views and cross-sections.

Reviewer #3

(Remarks to the Author)

Review Summary:

This paper provides a focused analysis of the ejecta displacement and radial rays and canyons surrounding the Schrödinger impact basin on the Moon. The "Grand Canyons" described are two deep, radial grooves formed by secondary craters in the inferred down-range direction of the impact structure with minor grooves in the up-range direction. Images and topography data combined with prior mapping of the ejecta are used to conduct measurements of the spatial patterns and dimensions of the radial canyons and the associated secondary craters and those within the ejecta of the basin. This photogeologic mapping of Schrödinger's ejecta is used to infer the trajectory of the impactor and the ejected material. Analytical models of ballistic trajectories and ejection velocities combined with scaling relationships are used to constrain the velocities and energy required to form the basin sculpture and secondary craters. The results indicate an impact trajectory from the SSE to NNW and that only a thin amount of ejecta or no ejecta from Schrödinger may be found in the candidate Artemis exploration zone.

The paper provides an interesting narrative of the processes and products of ejecta formation for the youngest impact basin on the Moon. While the paper does not use techniques that are particularly novel (many of the analytical methods and scaling relationships have been around for decades), the question of the contribution of ejecta sourced from Schrödinger (or other large basin or crater) to the Artemis exploration zones is an important one to answer. The paper's conclusions that there may be little to no Schrödinger ejecta in the Artemis zones is testable and could mean that material from South-Pole Aitken basin is more abundant near the surface and accessible to the Artemis missions and sampling strategy. The methods of measurements appear sound but could use some clarification, as described in the comments below. It is also a bit odd that so much emphasis of the paper is on the characteristics and process of formation of the deep secondary crater chains,

Vallis Schrödinger and Vallis Planck, when the perhaps the main goal—to determine the direction of impact and ejecta emplacement with implications for Artemis exploration zones—could have been mostly completed by simply describing the spatial patterns and intersections of ejecta rays with ejecta decay scaling laws. The dramatic descriptions of the topography of Vallis Schrödinger and Vallis Planck and the energy required for their formation are quite interesting when compared to natural and atomic process that are more familiar to us on Earth, but are largely superfluous to the end goal of determining the trajectory of impact and pattern and direction of ejecta emplacement.

Comments:

Lines 68-72, Lines 89-101, and Figure 3: The outlines of these secondary craters forming the canyons are fairly ambiguous (some with only partial arcs of the rim) and come with some level of measurement uncertainty of diameter and also degree of confidence in them being separate craters. Please include some discussion on the uncertainty in diameter measurement and how the individual craters were determined. For example, while the secondary craters certainly overlap, some of the crater outlines could be interpreted as a single larger crater instead of two overlapping, which would increase the inferred diameters and decrease the total number of craters identified.

Line 82: The provided 0.96 ratio value appears to be incorrect; should this be 0.196? It also isn't clear where in Pike 1974 where this ratio and cited uncertainties are found. Is uncertainty cited in a different paper from Pike or are these new calculations?

Lines 87-88: Please include in the methods section a brief description of how these d/D ratios for the secondary craters were determined. For example, were depths determined using a single profile (or multiple profiles) and maximum-minimum elevations along the profile? What is the spatial resolution of the SLDEM2015 gridded data product, and is this sufficient for the depth measurements?

Lines 125-128: Is there any other evidence for clustered impacts? Is there an analytical relationship for how fragment clusters might evolve with radius from the basin to further support the inference in transition to more signal fragments. Also, can fragment sizes be spatially variable (e.g., target heterogeneity) such that one ray consists of different sized fragments than a ray at a different azimuth?

Lines 133-134: The reference cites Schultz and Crawford, 2016, which suggests multiple phases of ejecta emplacement for large basins and oblique impacts: 1) early phase of ejecta (high speed and low angle), 2) decapitation of the impactor and associated scouring associated with early stages, and then 3) late-stage ejecta that is more radial to the basin center and covers the early stage ejecta and scour. Only the early ejecta patterns (#1, #2) were used to constrain the impact point. Under this cited framework, is the formation of Vallis Schrödinger and Vallis Planck being inferred as early stage ejecta that is decoupled from the transient cavity or later stages ejecta associated with growth of the transient cavity and whose radial trends and intersection, should be more basin-centered. I assume later stage since the canyons are not covered by ejecta and formed by distinct chains of secondaries connected with outer ray patterns. Indeed, Schultz and Crawford (2016) used the *uprange* early-stage ejecta patterns and intersection points to constrain the impact point, with the down-range pattern providing an estimate of the impactor diameter. So, how well can the later stage ejecta, which should be more centric to the basin center be used to infer impact trajectory? Along the same vein, inferring impact trajectory/direction from only two prominent late-stage rays seems relying on statistics of small numbers, when Schultz and Crawford show much variability in the intersection points. Indeed, the paper's Figure S1 shows this variability in the other minor crater rays; why are these not considered in the trajectory analysis?

Lines 153-163: The ejecta pattern appears to resemble a butterfly pattern bisected in the 33.5 (NNW) direction. This seems to further support the NNW trajectory.

Lines 164-172: It would be helpful to discuss how the opening of Schrödinger's peak ring in the inferred up-range direction is in contrast to modeling by Schultz and Crawford (2016) showing the peak ring opening in the down-range direction, with higher up-range topography attributed to oblique impacts for other basins (e.g., Moscoviense). This would seem to suggest that, pre-impact topography likely exhibits an even larger influence on peak-ring topographic development, possibly because the impact that formed Schrödinger wasn't as oblique as some other basin impacts and due to the influence of the large gradient in topography at the edge of SPA.

Figures:

Figure 3: It would be helpful to include transect lines on the images that show the locations for the profiles in Figure 2b and S4.

Figure 4: The measurement data used for the calculations behind this plot should be provided as supplemental material.

Methods:

Lines 355-358: Please clarify how many distance measurements are being made. It appears that perhaps there are four distance measurements, but based on the description in the methods it could be interpreted differently: 1) From secondary

crater (is this from the center of the crater?) to the basin center, 2) From secondary crater to the transient crater rim (where the trajectory from the basin center and the transient crater rim intersect), and 3) From secondary crater to the point at which the two largest rays intersect, 4) From secondary crater to the transient crater rim (where the trajectory from the rays' intersection point and the transient crater rim intersect). Or maybe it's just two distance measurements from the transient crater rim because that is what is needed for the velocity calculations? None of the figures show the transient crater rim intersection or these points in one map. Since this is important for the calculation, it would be helpful to include an additional supplement figure showing this. Please also provide values for these distance measurements in a table, including crater dimensions.

In addition, should the transient crater be concentric with the final rim-crest-diameter? Or offset toward the sub-impact point since the impact is inferred to be oblique and the cavity is evolving transiently? This would affect the distance and velocity calculations.

Lines 362: Please give the formula or state that it is a standard ballistic trajectory formula for airless bodies and point to an example reference.

Supplemental Material:

Figure S1: Why is one of the "Possible Crater Rays" (dashed orange) in the WNW section almost orthogonal to the basin-radial direction and another ray? Also, please label the blue grid on the map – are these latitude and longitudes and at what increments?

Figure S2: Suggest indicating that mapped rays were extended back through both points on the crater rim outline (in red). Also, are these great-circle paths to account for planetary curvature? If so, please indicate.

Version 1:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

The authors have done a reasonable job at addressing my comments.

Reviewer #2

(Remarks to the Author)

I have read the revisions for the manuscript entitled "Grand Canyons on the Moon" by Kring, Kallenborn, and Collins. The revisions to the article have made the work much more understandable and clear. My recommendation is that the article is ready for publication, but I have a small number of minor comments.

Line 34: Should "latest" be "late"?

Figure 4: Explicitly state what the black dashed line connecting the red points represents.

Line 220: Should "assessable" be "accessible"?

Line 232: Please add a quick statement or sentence about what conditions would lead to the added (red text) bearing possibility.

Reviewer #3

(Remarks to the Author)

The authors have sufficiently addressed my comments and concerns. The additional methods descriptions and supplemental material are greatly appreciated, which improve clarity and better support the presented observations and interpretations.

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Our replies to the reviewers' helpful comments, quoted here, are provided in [blue font](#).

REVIEWER COMMENTS

Reviewer #1 (Remarks to the Author):

Referee report for “Grand Canyons of the Moon” by Kring et al.

The manuscript is well written. Schrodinger is a well-studied lunar basin, and as such the manuscript expands on a wide body of literature. The actual new work presented in this manuscript is somewhat limited, but I think it would be an interesting addition given the implications for Artemis astronauts' exploration of the Moon. I suggest publication, pending some minor improvements listed below.

[Thank you.](#)

In 33: The manuscript builds on a large body of work regarding Schrodinger. It would be good to capture uncertainties, when possible. For instance, Schrodinger age is reported following an abstract (ref 24) and quoted with two decimal digits. It should be clear that the quoted age uncertainties are not realistic, and furthermore they are based on a chronology model that has been shown to be problematic. For comparison, a close inspection at Figure 4 in Morbidelli et al EPSC 2012 shows that for $N1 \sim 1e-2$ (Schrodinger), the age uncertainty can be up to ~ 300 Myr. A more recent model, Marchi et al Nat Geo 2021, shows a similar age spread in their Figure 1. See also Nesvorný et al ApJ 2022 (their Figure 2). I will get back to this point later.

[The latest paper in that series of models is Nesvorný et al. \(2023\) Early bombardment of the Moon: Connecting the lunar crater record to the terrestrial planet formation, Icarus 399 \(2023\) 115545. We consulted Alesandro Morbidelli who says the 2023 paper supersedes earlier work, including his own. The Nesvorný et al. \(2023\) paper indicates an uncertainty of \$\sim 150\$ Myr for a basin the age of Schrödinger, which we added to the text with a reference to Nesvorný et al. \(2023\). We also note, that in agreement with the spirit of the reviewer's comment, the text also pointed out that it is important to sample Schrödinger basin material to “test its estimated \$3.81^{+0.013}_{-0.014}\$ Ga age \(ref. 24\)” \(line 196 in the original manuscript\).](#)

Figure 3, b: One has to wonder if the marked circles are truly impact craters. With low ballistic angles (In 142), one may expect the craters to be non circular, and the fact that they are so closely packed seems unlikely to me to be individual impacts. In this regard, I wonder if the semi-circular appearance is instead due to interaction of the scouring and slumping of the surface due to high-velocity ejecta streams. This is not a critical point, but

the manuscript presents quite a bit of discussion considering the properties of these presumed craters and their impactors, while it might be these features were excavated in completely different ways.

The craters have clearly visible crater rims in images, which are also illustrated with two topographic profiles in an additional figure in Supplementary Information. Notionally, the interaction of ejecta curtains could “hide” a more elongate structure caused by low impact angles. However, the width of the canyons puts an upper limit on possible crater diameters.

Schultz and Crawford (2016) suggest ballistic flight angles of 20 to 45 degrees for material producing secondary craters. Gault and Wedekind (1978) found that craters remain circular down to 30 degrees. Thus, as long as the ballistic angle of ejecta making secondary craters is 30 to 45 degrees (which is within the allowable range we consider) circularity is expected. We added a sentence to the line 142 statement indicating the circularity of the crater suggests the angles may be in the upper part of the 20 to 45 degree range.

We note that a second hypothesis, that postulates the rays are lateral ejecta that is part of a butterfly pattern, implies (per Luo et al., 2022) ballistic launch angles of about 50 degrees, which would produce circular craters. We added a sentence with those angles to the text, too.

Ln 138: The comment about the distributed impact zone is interesting. The argument is a bit qualitative here, and I wish the authors had included an iSALE simulation (3D) to show this. If such a simulation were available, it would make a great addition to the paper.

This study is based on photogeological and analytical methods; any 3D simulation will have to wait for a subsequent study.

Ln 95-198: See previous comment on Schrodinger basin age. Further, there has been a great deal of work regarding the early lunar impact flux, and quoting NRC 2007 is outdated. Both sample analysis (see refs in Bottke and Norman 2017) and models (Nesvorný et al 2022; 2023) show that it is very unlikely there was a late impact spike. Still, the earliest lunar chronology is a key aspect of the Artemis’ science goals, and the manuscript would benefit from a more updated discussion. In general, the NRC report is presented as a justification for this work (Ln 21-23), but this is a stand-alone research paper that should present interesting science regardless of the NRC goals, so I suggest rephrasing such language.

The objectives identified in the NRC (2007) remain relevant, as it is essential to determine the cadence of impacts during the basin-forming epoch, which we do not believe has been resolved by Bottke and Norman (2017) and Nesvorný et al. (2022). Several subsequent NASA documents confirm/repeat that objective; good scholarship requires us to cite the original document, hence NRC (2007). We appreciate the reviewer’s suggestion to rephrase the language, but, respectfully, leave it as is. The key to confidently resolving uncertainties in the cadence of impacts is the identification of suitable sample sites on the lunar surface, collection of those samples, and return of them to Earth for analyses. The

current paper addresses geologic issues that affect the identification of suitable sample sites and that are directly relevant to ongoing site selection discussions for the Artemis III and IV missions.

Reviewer #2 (Remarks to the Author):

Review of “Grand Canyons on the Moon” by D. A. Kring, D. P. Kallenborn, and G. S. Collins

I have read and completed my review of “Grand Canyons on the Moon,” a manuscript submitted to Nature Communications for publication. I find the article straightforward and easy to digest, with important implications for the upcoming Artemis missions, as noted in the text. The work describes the secondary craters comprising two impressive canyons associated with Schrodinger Basin, Vallis Schrodinger and Vallis Planck. Using the secondary crater chains which presumably caused these two canyons, the authors calculate the energy required for their excavation. There are several comparisons between these two lunar canyons and the Grand Canyon on Earth, but these are primarily qualitative since the Grand Canyon formed via a very different process. However, the comparisons made in the manuscript are useful to give readers context on what is commonly intangible for most people.

We thank the reviewer for appreciating our effort to convey the dramatic topography of the lunar surface to readers.

My concerns are listed below, categorized into major and minor revisions for the authors.

Major Revisions

- Lines 124-126: The authors state that the larger secondary crater diameters in Vallis Schrodinger imply that they formed from clusters of fragments rather than larger intact fragments, based on scaling laws. However, this canyon also falls completely within Schrodinger’s continuous ejecta blanket. Is this conclusion robust? Do the scaling laws hold for impact effects that close to the point of contact?

While the canyons are close to the crater in a relative sense, in an absolute sense they are several hundred kilometers away and were formed by impacts at speeds close to 1 km/s. This speed is only just below the speed range of the impact experiments that have been used to develop the crater scaling relationships that we apply in this work (e.g., Schmidt and Housen, 1987). Moreover, these scaling laws have been shown to be appropriate for some conditions at even lower impact speeds (e.g., Gault and Wedekind, 1978; Hartmann, 1985; Holsapple and Schmidt, 1982; Ormö et al., 2015; Yamamoto et al., 2006). We added these details to the methods section.

Clusters of secondary craters are commonly observed (e.g., Lucchitta, 1977; Schultz and Gault, 1985). Further, those clusters of fragments spread out with radial distance beyond the continuous ejecta blanket (Schultz and Gault, 1985). Thus, it is logical that clusters closer to the point of impact (i.e., within the continuous ejecta blanket) would have a

smaller spread (be more tightly clustered) and produce simple craters like those observed. These details and additional references were added to the text.

- Lines 143-144: How is this energy calculated (1.68×10^{20} J)? Relatedly, what is the difference between this calculation and the one for line 147 (3.39×10^{20} J). I am guessing the larger number reflects if there was a continuous line of identifiable secondary craters for the length of Vallis Schrodinger? The comparison is not clear.

The energy is calculated using the kinetic energy formula for the determined impactor masses and measured distances they travelled (which provides velocities, as described in the methods section). The first number reflects the sum of the energy necessary to produce the identified craters in Vallis Schrödinger. But, as the paper notes, well-preserved craters do not cover the whole length of Vallis Schrödinger. As stated in the paper, assuming a similar distribution of craters along the whole length, a minimum kinetic energy of 3.39×10^{20} J is necessary to produce Vallis Schrödinger. As cratering was the method of excavation, that is straightforward reasoning.

- Lines 156-159: The authors mention a local slope in the vicinity of Schrodinger Basin while discussing the asymmetry of the ejecta blanket from the north to the south. This is an interesting idea, were any calculations done to determine if this slope contributes to the asymmetry? Could the upward slope to the northwest notably impede ejecta deposition?

That is a good thing to check. Upward slopes where ejecta is foreshortened are <20 degrees (and often <10 degrees), which is less than the ejecta launch angles. Thus, upward slope is unlikely to block ejecta deposition.

Minor Revisions:

- Lines 90-92: Change sentence to “Vallis Planck does not show continuous secondary cratering everywhere and appears to be modified by the collapse of canyon walls.” For more easy reading (change in bold).

We replaced the sentence as suggested, but with a caveat. The verb “show” might be misinterpreted to mean that secondary cratering did not produce some sections of the Vallis. Instead of the word “show,” we modified the sentence with the verb “preserved.”

- Line 102: Please reference the Methods section here, as it is currently unclear how these numbers are calculated.

Done.

- Lines 150-151: Please put references for the different comparisons in the main text

Done.

- Line 165: I believe the reference should go at the end of the sentence.

Done.

- Lines 180-181: Please be more explicit about the “two greatest uncertainties,” I presume that this refers to the presence of the Schrodinger ejecta blanket overlying SPA material, and possibly if any ejecta from Amundsen-Ganswindt Basin will also contaminate a possible SPA collection? I find this very unclear, however.

The text was amended for clarity and now reads “...needed is a similar assessment of the distribution of ejecta around the Amundsen-Ganswindt basin which has the potential to cover SPA ejecta, too.

- Line 201: Change sentence to “...so a cross-section of the Moon to a depth of ~100 km may be assessable, albeit dismembered.” (change in bold)

Done.

- Line 204: Change sentence to “Excavated SPA material and any primordial crust can be used to test the lunar magma ocean hypothesis for planetary differentiation and the giant impact hypothesis for the origin of the Earth-Moon system, among many other objectives.” (change in bold)

Done.

- Supplementary Figures 1 and 2: These would be more informative if there were 2 panels per figure, one with the annotations and one without. It is hard to verify the author’s interpretation of the linear features without a “clean” version to review.

A side-by-side view replaces the first of those Supplementary Figures (originally labeled 1, but now labeled 2, because of the addition of a new Supplementary Figure 1). We did not repeat that for the next figure, because it would have duplicated the view that a reader can see in the new Supplementary Figure 2.

- Supplementary Figures 1-4, Figures 2-3: Please add N/E/S/W annotation to the map views and cross-sections.

When working in a southern circumpolar region, north radiates in all directions from the pole. Thus, a single north-indicating arrow on a map is not appropriate. To help readers understand cardinal directions in the region, we added to the Figure 1 caption that “North radiates in all directions from the south pole.” We added similar notes to the relevant Supplementary Figures. For clarity, we also inserted a new Supplementary Figure (#1) that

shows clearly the location of the Schrödinger basin relative to the south pole and the northward-directed meridians that radiate from the south pole. We might add that ‘south pole’ is not a formal (IAU) geographic name on the Moon, so it is not capitalized like it is on Earth.

Reviewer #3 (Remarks to the Author):

Review Summary:

This paper provides a focused analysis of the ejecta displacement and radial rays and canyons surrounding the Schrödinger impact basin on the Moon. The “Grand Canyons” described are two deep, radial grooves formed by secondary craters in the inferred down-range direction of the impact structure with minor grooves in the up-range direction. Images and topography data combined with prior mapping of the ejecta are used to conduct measurements of the spatial patterns and dimensions of the radial canyons and the associated secondary craters and those within the ejecta of the basin. This photogeologic mapping of Schrödinger’s ejecta is used to infer the trajectory of the impactor and the ejected material. Analytical models of ballistic trajectories and ejection velocities combined with scaling relationships are used to constrain the velocities and energy required to form the basin sculpture and secondary craters. The results indicate an impact trajectory from the SSE to NNW and that only a thin amount of ejecta or no ejecta from Schrödinger may be found in the candidate Artemis exploration zone.

The paper provides an interesting narrative of the processes and products of ejecta formation for the youngest impact basin on the Moon. While the paper does not use techniques that are particularly novel (many of the analytical methods and scaling relationships have been around for decades), the question of the contribution of ejecta sourced from Schrödinger (or other large basin or crater) to the Artemis exploration zones is an important one to answer. The paper’s conclusions that there may be little to no Schrödinger ejecta in the Artemis zones is testable and could mean that material from South-Pole Aitken basin is more abundant near the surface and accessible to the Artemis missions and sampling strategy. The methods of measurements appear sound but could use some clarification, as described in the comments below. It is also a bit odd that so much emphasis of the paper is on the characteristics and process of formation of the deep secondary crater chains, Vallis Schrödinger and Vallis Planck, when the perhaps the main goal—to determine the direction of impact and ejecta emplacement with implications for Artemis exploration zones—could have been mostly completed by simply describing the spatial patterns and intersections of ejecta rays with ejecta decay scaling laws. The dramatic descriptions of the topography of Vallis Schrödinger and Vallis Planck and the energy required for their formation are quite interesting when compared to natural and atomic process that are more familiar to us on Earth, but are largely superfluous to the end goal of determining the trajectory of impact and pattern and direction of ejecta emplacement.

Comments:

Lines 68-72, Lines 89-101, and Figure 3: The outlines of these secondary craters forming the canyons are fairly ambiguous (some with only partial arcs of the rim) and come with some level of measurement uncertainty of diameter and also degree of confidence in them being separate craters. Please include some discussion on the uncertainty in diameter measurement and how the individual craters were determined. For example, while the secondary craters certainly overlap, some of the crater outlines could be interpreted as a single larger crater instead of two overlapping, which would increase the inferred diameters and decrease the total number of craters identified.

As suggested, we expanded measurement details in the methods section. In summary, multiple measurements of secondary crater diameters were made with a variation that was generally <5%.

Line 82: The provided 0.96 ratio value appears to be incorrect; should this be 0.196? It also isn't clear where in Pike 1974 where this ratio and cited uncertainties are found. Is uncertainty cited in a different paper from Pike or are these new calculations?

Thank you for catching the typographical error, which we fixed (changing 0.96 to 0.196).

The source of that number and uncertainties are data in Pike (1974), as cited in the submitted manuscript. We acknowledge, however, that it was Pike (1980) that presented the data in the format we use. Thus, we changed the reference from Pike (1974) to Pike (1980), the latter of which will then refer readers to Pike (1974) for the data.

Lines 87-88: Please include in the methods section a brief description of how these d/D ratios for the secondary craters were determined. For example, were depths determined using a single profile (or multiple profiles) and maximum-minimum elevations along the profile? What is the spatial resolution of the SLDEM2015 gridded data product, and is this sufficient for the depth measurements?

The requested details were added to the methods section. The SLDEM has a typical vertical accuracy of ~3 to 4 m which is sufficient for the depth measurements.

Lines 125-128: Is there any other evidence for clustered impacts? Is there an analytical relationship for how fragment clusters might evolve with radius from the basin to further support the inference in transition to more signal fragments. Also, can fragment sizes be spatially variable (e.g., target heterogeneity) such that one ray consists of different sized fragments than a ray at a different azimuth?

The issue of clustered impacts as a function of radial distance was noted by Reviewer #1 and addressed as described above.

Regarding target heterogeneity: While notionally target lithologies may control fragment sizes (e.g., as at Meteor Crater), that is not evident in our own data. As shown in Figure 4, the transition in fragment size is not only evident between the rays, but is also evident within the Vallis Planck data (see the triangular symbols). Moreover, no evidence of that has been detected in studies of lunar crater rays. Indeed, consistency in fragment size as a function of distance is one of the criteria used to discriminate secondary craters from primary craters (e.g., Singer et al., 2020). We added a paragraph saying as much.

Lines 133-134: The reference cites Schultz and Crawford, 2016, which suggests multiple phases of ejecta emplacement for large basins and oblique impacts: 1) early phase of ejecta (high speed and low angle), 2) decapitation of the impactor and associated scouring associated with early stages, and then 3) late-stage ejecta that is more radial to the basin center and covers the early stage ejecta and scour. Only the early ejecta patterns (#1, #2) were used to constrain the impact point. Under this cited framework, is the formation of Vallis Schrödinger and Vallis Planck being inferred as early stage ejecta that is decoupled from the transient cavity or later stages ejecta associated with growth of the transient cavity and whose radial trends and intersection, should be more basin-centered. I assume later stage since the canyons are not covered by ejecta and formed by distinct chains of secondaries connected with outer ray patterns. Indeed, Schultz and Crawford (2016) used the *uprange* early-stage ejecta patterns and intersection points to constrain the impact point, with the down-range pattern providing an estimate of the impactor diameter. So, how well can the later stage ejecta, which should be more centric to the basin center be used to infer impact trajectory? Along the same vein, inferring impact trajectory/direction from only two prominent late-stage rays seems relying on statistics of small numbers, when Schultz and Crawford show much variability in the intersection points. Indeed, the paper's Figure S1 shows this variability in the other minor crater rays; why are these not considered in the trajectory analysis?

As described in the original manuscript, the two prominent rays are produced early in the excavation process (lines 132-133 in the original manuscript) and several smaller rays produced later in the process (lines 137-138 in the original manuscript); all rays, including those in Figure S1 (lines 138-140 in the original manuscript), were used in the analysis.

Late ejecta may have filled in part of the rays; i.e., the rays may have once extended closer to the basin rim. Standard ejecta thickness calculations suggest total ejecta thickness at the beginning of the still-visible Vallis Schrödinger would be about 300 to 400 m in the nearly 2-km-deep chasm (and, thus, partially responsible for low d/D values), but only a few tens of meters thick at the outer edge of Vallis Schrödinger and, thus, would not significantly bury that portion the ray.

Lines 153-163: The ejecta pattern appears to resemble a butterfly pattern bisected in the 33.5 (NNW) direction. This seems to further support the NNW trajectory.

We amended the text to say so.

Lines 164-172: It would be helpful to discuss how the opening of Schrödinger's peak ring in the inferred up-range direction is in contrast to modeling by Schultz and Crawford (2016) showing the peak ring opening in the down-range direction, with higher up-range topography attributed to oblique impacts for other basins (e.g., Moscoviense). This would seem to suggest that, pre-impact topography likely exhibits an even larger influence on peak-ring topographic development, possibly because the impact that formed Schrödinger wasn't as oblique as some other basin impacts and due to the influence of the large gradient in topography at the edge of SPA.

Done.

Figures:

Figure 3: It would be helpful to include transect lines on the images that show the locations for the profiles in Figure 2b and S4.

Done.

Figure 4: The measurement data used for the calculations behind this plot should be provided as supplemental material.

Done. Data appear as Supplementary Table 1.

Methods:

Lines 355-358: Please clarify how many distance measurements are being made. It appears that perhaps there are four distance measurements, but based on the description in the methods it could be interpreted differently: 1) From secondary crater (is this from the center of the crater?) to the basin center, 2) From secondary crater to the transient crater rim (where the trajectory from the basin center and the transient crater rim intersect), and 3) From secondary crater to the point at which the two largest rays intersect, 4) From secondary crater to the transient crater rim (where the trajectory from the rays' intersection point and the transient crater rim intersect). Or maybe it's just two distance measurements from the transient crater rim because that is what is needed for the velocity calculations? None of the figures show the transient crater rim intersection or these points in one map. Since this is important for the calculation, it would be helpful to include an additional supplement figure showing this. Please also provide values for these distance measurements in a table, including crater dimensions.

The methods section was amended as suggested for clarification.

In addition, should the transient crater be concentric with the final rim-crest-diameter? Or

offset toward the sub-impact point since the impact is inferred to be oblique and the cavity is evolving transiently? This would affect the distance and velocity calculations.

As described in the paper (methods, lines 355-359 in the original manuscript), four different distances were used in the calculations and encompass this particular uncertainty.

Lines 362: Please give the formula or state that it is a standard ballistic trajectory formula for airless bodies and point to an example reference.

The formula was added to the methods.

Supplemental Material:

Figure S1: Why is one of the “Possible Crater Rays” (dashed orange) in the WNW section almost orthogonal to the basin-radial direction and another ray? Also, please label the blue grid on the map – are these latitude and longitudes and at what increments?

Good catch; the dashed orange line was a processing artifact and deleted.

The blue gridded lines represent distance segments in radii from the basin center (not latitude or longitude) were used to determine if there were systematic geographic patterns among secondary features. Text was added for clarification.

Figure S2: Suggest indicating that mapped rays were extended back through both points on the crater rim outline (in red). Also, are these great-circle paths to account for planetary curvature? If so, please indicate.

The lines trace the rays as they appear on a Lambert Azimuthal Equal Area Projection, as indicated at the top of the map.

POINT-BY-POINT REPLY TO REVIEWER COMMENTS

Reviewer #1 (Remarks to the Author): The authors have done a reasonable job at addressing my comments.

Thank you.

Reviewer #2 (Remarks to the Author): I have read the revisions for the manuscript entitled “Grand Canyons on the Moon” by Kring, Kallenborn, and Collins. The revisions to the article have made the work much more understandable and clear. My recommendation is that the article is ready for publication, but I have a small number of minor comments.

Line 34: Should “latest” be “late”?

Thank you; spelling corrected.

Figure 4: Explicitly state what the black dashed line connecting the red points represents.

Done.

Line 220: Should “assessable” be “accessible”?

Thank you; spelling corrected.

Line 232: Please add a quick statement or sentence about what conditions would lead to the added (red text) bearing possibility.

Done.

Reviewer #3 (Remarks to the Author): The authors have sufficiently addressed my comments and concerns. The additional methods descriptions and supplemental material are greatly appreciated, which improve clarity and better support the presented observations and interpretations.

Thank you.