Peer Review File

Manuscript Title: About the Lunar solid inner core and the mantle overturn

Reviewer Comments & Author Rebuttals

Reviewer Reports on the Initial Version:

Referee #1:

Review of Ms # 2022-03-04980A: Briaud, Ganino, Fienga, Mémin and Rambaux: About the Lunar solid inner core and the mantle overturn.

This paper claims to provide clear evidence of a deep lunar mantle overturn, existence of a partially molten ilmenite-rich low-velocity zone at the boundary between the core and the mantle, and a solid iron-light element alloys inner core.

The paper is original and the content is potentially significant. The text is quite well written.

A passage of fundamental importance for the paper is found in line 151-156: Based on results from earlier published studies, the authors estimate that "...the models including a solid inner core have a melting rate below 30% while the models without inner core present a melting rate greater than 30%." While their line of reasoning behind this conclusion seems entirely reasonable, the following statement: "A melting rate larger than 30% would drive a drastic decrease in the shear wave velocity [23] incompatible with seismic models" is problematic.

The variability of the published seismic velocity and density models cannot be viewed simplistically. The resolution and uncertainty of the models are interdependent, and they depend on the parameterizations (number of layers, hard constraints on parameters, etc.), as well as on prior constraints with a smoothing effect. Smaller layer thicknesses result in higher resolution, but larger uncertainties. Even if the real shear wave velocity shows a drastic decrease in some depth range, you may not be able to see it in the published models and their uncertainty estimates. It all depends on their layer thicknesses (or density of control points).

For this reason I find the main conclusions of this paper rather risky. Given their importance for our understanding of the Moon, a much more careful analysis of the seismic constraints is required, before firm conclusions can be made. The (combined) resolution and uncertainty of the seismic models must be taken explicitly into account.

In light of the above considerations, I recommend that the paper is rejected and referred to a domain-specific journal where all the details can be presented in more detail.

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Referee #2:

The authors presented a modeling study of lunar tidal deformation to place constraints on lunar

interior structure by using observations of tidal deformation (i.e., Love numbers h2 and k2), dissipation, and moment of inertia. The lunar structure model consists of different layers with density, viscosity and elastic parameters. The tidal deformation models are computed using a Monte Carlo method to sample the parameter space for layer thickness, density, viscosity and elastic parameters. The calculations show a number of important results. The first is that an solid inner core is required, and the second is that the low-velocity zone (LVZ) above the core-mantle boundary has a larger density but smaller viscosity than the overlying mantle.
The characteristics of the LVZ are consistent with the deep lunar mantle overturn hypothesis in which ilmenite-bearing cumulates sink to the core-mantle boundary following the solidification of lunar magma ocean. The calculations determine the preferred thickness, density, viscosity and elastic parameters of these layers and the ranges of possible values. These results of basic lunar parameters can be of important use for future studies of lunar interior dynamics and volcanism. I think that the results can be published in Nature and that the paper can be strengthened if the authors address the following questions.

1) In Table 1, one of the parameters is mantle viscosity. This parameter is fixed as 10^21 Pas and has not varied in the Monte Carlo simulations. It would be helpful to discuss the effect of varying this parameter on the results.

2) It would be helpful to have some general discussions on how each observable depends on the model parameters. For example, what model parameters control the dissipation or h2, k2, …?

Minor points:
1) Line 83: “no viscosity”. Do you mean “purely elastic with infinite viscosity”? No viscosity could mean inviscid.

2) Lines 106-107. Is this comparison of lunar core density with the Earth's done at the same pressure?

3) Lines 112-115. I am not sure if the similarity of the ratio of the inferred radii of the outer core to the inner core for the Moon to the ratio of those radii for the Earth’s core is of much significancy. The Earth’s inner core growth is controlled by the cooling history of the Earth, which could be very different from that of the Moon.

4) Line 122: “including or not an inner core”. How about replace it “with or without an inner core”?

5) Lines 133-136. These two sentences are unclear. Did you mean that with out an inner core, the deduced LVZ viscosity would be too small? Consider re-writing them.

6) Line 153. “melting rate”. From subsequent sentences, the melting rate is for the LVZ, but it is unclear what the melting rate is referred to in this sentence where it is first discussed.

7) Line 250. Appendix A. Remove “an”

8) Line 316-317, Appendix C. This is an incomplete sentence.

Author Rebuttals to Initial Comments

Reviewer 1

This paper claims to provide clear evidence of a deep lunar mantle overturn, existence of a partially molten ilmenite-rich low-velocity zone at the boundary between the core and the mantle, and a solid iron-light element alloys inner core. The paper is original and the content is potentially significant. The text is quite well written. A passage of fundamental importance for the paper is found in line 151-156: Based on results from earlier published studies, the authors estimate that "...the models including a solid inner core have a melting rate below 30% while the models without inner core present a melting rate greater than 30%." While their line of reasoning behind this conclusion seems entirely reasonable, the following statement: "A melting rate larger than 30% would drive a drastic decrease in the shear wave velocity [23] incompatible with seismic models" is problematic. The variability of the published seismic velocity and density models cannot be viewed simplistically. The resolution and uncertainty of the models are interdependent, and they depend on the parameterizations (number of layers, hard constraints on parameters, etc.), as well as on prior constraints with a smoothing effect. Smaller layer thicknesses result in higher resolution, but larger uncertainties. Even if the real shear wave velocity shows a drastic decrease in some depth range, you may not be able to see it in the published models and their uncertainty estimates. It all depends on their layer thicknesses (or density of control points). For this reason I find the main conclusions of this paper rather risky. Given their importance for our understanding of the Moon, a much more careful analysis of the seismic constraints is required, before firm conclusions can be made. The (combined) resolution and uncertainty of the seismic models must be taken explicitly into account. In light of the above considerations, I recommend that the paper is rejected and referred to a domain-specific journal where all the details can be presented in more detail.

We agree with the reviewer. We thank the reviewer for his/her fruitful comment on the variability of seismic models from previous studies. Our former argumentation relied on an old reference [1] and is not sustained by comparisons to most recent analysis [2]. Based on these comments, we have deeply modified the manuscript and added new arguments in favor of a deep mantle overturn and a solid inner core.
The dispersion of the modeled shear-wave velocity profiles in the literature is indeed important and can not be used for properly ruling out the diversity of geodesic models we produced. The argument based on Vs profiles is then not used anymore for this new version as well as the melting rate proposed by [1]. We consider, instead, the thermodynamic evolution of the LVZ for different hypothesis of chemical compositions, temperature and depth profiles deduced from our geophysical models.
We performed thus thermodynamic simulations using the Perple_X program, exploring a realistic range of LVZ compositions, from dunite, Earth-like mantle composition (ilminite-free cumulates) to different ilmenite cumulates as shown in Fig 1 and 6 of the current version of the manuscript. In comparison with the previous version, we consider additional possible petrological types for the LVZ (dunite, lherzolite, lherzolite with 8% Ilmenite and 100% Ilmenite cumulates). The choice for these assemblages is driven by the published values of the corresponding activitation enthalpies. From these simulations, it turns out that only thermodynamic models with an inner core and with an ilmenite-rich LVZ fit with our geophysical constraints. We rule out profiles without solid inner core and with an ilmenite-free LVZ. These new results enhance also the scenario of the global mantle overturn.

Reviewer 2

The authors presented a modeling study of lunar tidal deformation to place constraints on lunar interior structure by using observations of tidal deformation (i.e., Love numbers h2 and k2), dissipation, and moment of inertia. The lunar structure model consists of different layers with density, viscosity and elastic parameters. The tidal deformation models are computed using a Monte Carlo method to sample the parameter space for layer thickness, density, viscosity and elastic parameters. The calculations show a number of important results. The first is that an solid inner core is required, and the second is that the low-velocity zone (LVZ) above the core-mantle boundary has a larger density but smaller viscosity than the overlying mantle. The characteristics of the LVZ are consistent with the deep lunar mantle overturn hypothesis in which ilmenite-bearing cumulates sink to the core-mantle boundary following the solidification of lunar magma ocean. The calculations determine the preferred thickness, density, viscosity and elastic parameters of these layers and the ranges of possible values. These results of basic lunar parameters can be of important use for future studies of lunar interior dynamics and volcanism. I think that the results can be published in Nature and that the paper can be strengthened if the authors address the following questions.

a) In Table 1, one of the parameters is mantle viscosity. This parameter is fixed as 10^21 Pas and has not varied in the Monte Carlo simulations. It would be helpful to discuss the effect of varying this parameter on the results.

We added the section 2.1.2 addressing the question. What we show here is that a mantle viscosity greater than 10^{20} Pa·s is indeed compatible with our evaluation of the geophysical constraints (Love number k_2 and the monthly and yearly quality factor Q (see Fig. 5)). Other lower viscosity ranges ($<10^{20}$ Pa·s) are however out of the comparisons. But what we also show on Fig. 6 is that even in taking the range of compatible mantle viscosity spanning from 10^{20} Pa·s to 10^{24} Pa·s, the results are the same for the profiles of temperature versus activation enthalpy and temperature versus densities estimated with the *Perple_X* program [3].

b) It would be helpful to have some general discussions on how each observable depends on the model parameters. For example, what model parameters control the dissipation or h2, k2, . . . ?

We have added in section 2.1.3 a discussion related to the sensitivity of the deformation variables (Love numbers k_2 and h_2 and the yearly and monthly quality factors) but also the total mass and Moon moment of inertia to variations in the parameters of the layers. As one can on Fig. 7, it turns out that, with no surprise, the total mass and moment of inertia are first, driven by the mantle radii and second, driven by the inner core radii and densities. The Love numbers k_2 and h_2 are sensitive to mantle rigidities and radii. Maybe, more surprisingly, the quality factors are more sensitive to the characteristics of the deepest layers, mainly the outer and inner core.

Minor comments

a) Line 83: "no viscosity". Do you mean "purely elastic with infinite viscosity"? No viscosity could mean inviscid.

Yes. It is indeed this. So we modified the text accordingly.

b) Lines 106-107. Is this comparison of lunar core density with the Earth's done at the same pressure?

No, it is not and the reviewer is indeed right in stressing that these comparisons should be done in the same context of pressure and temperature. As this comment is not very important for the rest of the discussion, we remove the comparison between Earth core density and Moon core density.

c) Lines 112-115. I am not sure if the similarity of the ratio of the inferred radii of the outer core to the inner core for the Moon to the ratio of those radii for the Earth's core is of much significant. The Earth's inner core growth is controlled by the cooling history of the Earth, which could be very different from that of the Moon.

These comparisons should indeed be more argumentative. Again as it is not of crucial importance for the rest of the discussion we remove the sentence.

d) Line 122: “including or not an inner core”. How about replace it “with or without an inner core”?

We agree. We modified the text accordingly.

e) Lines 133-136. These two sentences are unclear. Did you mean that with out an inner core, the deduced LVZ viscosity would be too small? Consider re-writing them.

We agree. We added in the text the corresponding values of viscosities for the two layers and the two cases (with and without inner core). We hope the sentence is then clearer.

f) Line 153. “melting rate”. From subsequent sentences, the melting rate is for the LVZ, but it is unclear what the melting rate is referred to in this sentence where it is first discussed.

The paragraph about the melting rate has been removed as this argument was not used anymore in the argumentation.

g) Line 250. Appendix A. Remove “an”

Thank you. we removed the unnecessary ”an”

h) Line 316-317, Appendix C. This is an incomplete sentence.

We agree. We modified the appendix. It is now the sub-section 2.2.1

References

[1] R. C. Weber, P.-Y. Lin, E. J. Garnero, Q. Williams, and P. Lognonné, “Seismic detection of the lunar core,” *science*, vol. 331, no. 6015, pp. 309–312, 2011.

[2] R. F. Garcia, A. Khan, M. Drilleau, L. Margerin, T. Kawamura, D. Sun, M. A. Wieczorek, A. Rivoldini, C. Nunn, R. C. Weber, *et al.*, “Lunar seismology: An update on interior structure models,” *Space Science Reviews*, vol. 215, no. 8, pp. 1–47, 2019.

[3] J. Connolly, “Multivariable phase diagrams; an algorithm based on generalized thermodynamics,” *American Journal of Science*, vol. 290, no. 6, pp. 666–718, 1990.

Reviewer Reports on the First Revision:

Referee #1:

Review of revised Ms # 2022-03-04980B: Briaud, Ganino, Fienga, Mémin and Rambaux: About the Lunar solid inner core and the mantle overturn.

In the revised manuscript, the authors have abandoned their key argument based on shear wave velocity profiles, obtained from inversion of the Apollo seismic data. Instead, they have based their conclusions on simulations of the thermodynamic evolution of the low-velocity zone at the core-mantle boundary for different hypothesis of chemical compositions, temperature and depth profiles deduced from other geophysical models.

In my view, this is a considerable improvement of the paper. The new manuscript presents a well-thought-out piece of work, based on a simple, yet thorough, data analysis with interesting and important results. The authors carefully communicates the assumptions and uncertainties of their results, so that the reader can draw his/her own conclusion about the validity of their interpretations.

I recommend that the paper, after the revision presented here, is accepted for publication.

Klaus Mosegaard

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Referee #2:

The authors revised the manuscript significantly from the initial submission. The revision generally improves the paper and strengthens their original conclusions for a solid inner core and ilminite-rich LVZ. The main revision is to add thermodynamic constraint on mantle composition of LVZ, by using Perple_X modeling. The authors addressed adequately my main concern on the effect of the choice of mantle viscosity in the original submission. To reiterate my assessment from my original review, the results of basic lunar parameters presented in this study can be of important use for future studies of lunar interior dynamics and volcanism, given that these results are constrained by all the available geophysical and thermodynamics constraints.

One minor comment is that uncertainties should be added to the inner core radius and density in the abstract. The main text includes uncertainties for all the results, and the abstract should too.

Author Rebuttals to First Revision:

Referee #1:

We thank Klaus Mosegaard for his kind comment on the manuscript.

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I recommend that the paper, after the revision presented here, is accepted for publication.

Klaus Mosegaard

Referee #2:

We thank the anonymous reviewer for his/her suggestions in improving the manuscript. We have added the uncertainties of the inner core radius and density in the first paragraph of the manuscript.

The authors revised the manuscript significantly from the initial submission. The revision generally improves the paper and strengthens their original conclusions for a solid inner core and ilminite-rich LVZ. The main revision is to add thermodynamic constraint on mantle composition of LVZ, by using Perple_X modeling. The authors addressed adequately my main concern on the effect of the choice of mantle viscosity in the original submission. To reiterate my assessment from my original review, the results of basic lunar parameters presented in this study can be of important use for future studies of lunar interior dynamics and volcanism, given that these results are constrained by all the available geophysical and thermodynamics constraints.

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