nature portfolio

Peer Review File

Lunar-like silicate material forms the Earth quasi-satellite (469219) 2016 HO3 Kamo`oalewa

Web links to the author's journal account have been redacted from the decision letters as indicated to maintain confidentiality.

28th Jun 21

Dear Mr Sharkey,

Please allow me to apologise for the delay in sending a decision on your manuscript titled "Characterizing Earth Quasi-Satellite (469219) 2016 HO3 Kamo`oalewa". It has now been seen by 2 reviewers, and I include their comments at the end of this message. They find your work of interest, but some important points are raised. We are interested in the possibility of publishing your study in Communications Earth & Environment, but would like to consider your responses to these concerns and assess a revised manuscript before we make a final decision on publication.

We therefore invite you to revise and resubmit your manuscript, along with a point-by-point response that takes into account the points raised. Please highlight all changes in the manuscript text file.

In particular, please ensure that you expand your discussion on the potential origins of Kamo'oalewa and ensure that your interpretations are informed by comparisons with relevant solar system materials and calculations using up-to-date information.

We are committed to providing a fair and constructive peer-review process. Please don't hesitate to contact us if you wish to discuss the revision in more detail.

Please use the following link to submit your revised manuscript, point-by-point response to the referees' comments (which should be in a separate document to any cover letter) and the completed checklist:
[link redacted]
** This url links to your confidential home page and associated information about manuscripts you may have submitted or be reviewing for us. If you wish to forward this email to co-authors, please delete the link to your homepage first **

We hope to receive your revised paper within six weeks; please let us know if you aren't able to submit it within this time so that we can discuss how best to proceed. If we don't hear from you, and the revision process takes significantly longer, we may close your file. In this event, we will still be happy to reconsider your paper at a later date, as long as nothing similar has been accepted for publication at Communications Earth & Environment or published elsewhere in the meantime.

We understand that due to the current global situation, the time required for revision may be longer than usual. We would appreciate it if you could keep us informed about an estimated timescale for resubmission, to facilitate our planning. Of course, if you are unable to estimate, we are happy to accommodate necessary extensions nevertheless.

Please do not hesitate to contact me if you have any questions or would like to discuss these revisions further. We look forward to seeing the revised manuscript and thank you for the opportunity to review your work.

Best regards,

Joe Aslin

Associate Editor,
Communications Earth & Environment
https://www.nature.com/commsenv/
Twitter: @CommsEarth

EDITORIAL POLICIES AND FORMATTING

We ask that you ensure your manuscript complies with our editorial policies. Please ensure that the following formatting requirements are met, and any checklist relevant to your research is completed and uploaded as a Related Manuscript file type with the revised article.

Editorial Policy: Policy requirements

Furthermore, please align your manuscript with our format requirements, which are summarized on the following checklist:
Communications Earth & Environment formatting checklist

and also in our style and formatting guide Communications Earth & Environment formatting guide .

*** DATA: Communications Earth & Environment endorses the principles of the Enabling FAIR data project (http://www.copdess.org/enabling-fair-data-project/). We ask authors to make the data that support their conclusions available in permanent, publically accessible data repositories. (Please contact the editor if you are unable to make your data available).

All Communications Earth & Environment manuscripts must include a section titled "Data Availability" at the end of the Methods section or main text (if no Methods). More information on this policy, is available at http://www.nature.com/authors/policies/data/data-availability-statements-data-citations.pdf.

In particular, the Data availability statement should include:
- Unique identifiers (such as DOIs and hyperlinks for datasets in public repositories)
- Accession codes where appropriate
- If applicable, a statement regarding data available with restrictions
- If a dataset has a Digital Object Identifier (DOI) as its unique identifier, we strongly encourage including this in the Reference list and citing the dataset in the Data Availability Statement.

DATA SOURCES: All new data associated with the paper should be placed in a persistent repository where they can be freely and enduringly accessed. We recommend submitting the data to discipline-specific, community-recognized repositories, where possible and a list of recommended repositories is provided at <a

href="http://www.nature.com/sdata/policies/repositories">http://www.nature.com/sdata/policies/repositories.

If a community resource is unavailable, data can be submitted to generalist repositories such as figshare or Dryad Digital Repository. Please provide a unique identifier for the data (for example a DOI or a permanent URL) in the data availability statement, if possible. If the repository does not provide identifiers, we encourage authors to supply the search terms that will return the data. For data that have been obtained from publically available sources, please provide a URL and the specific data product name in the data availability statement. Data with a DOI should be further cited in the methods reference section.

Please refer to our data policies at http://www.nature.com/authors/policies/availability.html.

REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

Journal: Communications Earth & Environment

Manuscript #: COMMSENV-21-0303-T

Title: Characterizing Earth Quasi-Satellite (469219) 2016 HO3 Kamo`oalewa

Authors: Benjamin N. L. Sharkey, Vishnu Reddy, Renu Malhotra, Audrey Thirouin, Olga Kuhn, Albert Conrad, Barry Rothberg, Juan A. Sanchez, David Thompson, Christian Veillet

Based on the analysis of a reflectance spectrum of Earth's quasi-satellite 469219 Kamo`oalewa (2016 HO3), the authors of this manuscript carry out the fundamental and very important task of physically characterizing such an interesting asteroid. Few Earth co-orbital asteroids have been observed spectroscopically as they are rather challenging targets in terms of brightness and visibility windows. After applying a solid, sound, and reliable methodology, the authors arrived to a novel, original, and groundbreaking result that entertains the possibility of an origin of Kamo`oalewa as lunar ejecta. Lunar craters are well understood and lunar meteorites are also well documented. The tentative result presented in this manuscript links both subjects, unveiling a possible dynamical pathway from the surface of the Moon to the surface of our
planet. If confirmed, it would be a truly revolutionary result of great interest for the entire scientific community.

According to the authors, the reflectance spectrum of Kamo`oalewa shows features consistent with a silicate-based chemical composition of its surface involving a significant level of reddening that is higher than the typical one
among asteroids in the inner solar system. Then the authors further elaborate on this, finding that the best matching corresponds to that of the spectra of lunar-like silicates, which leads them to infer

a possible lunar origin. In
summary, I believe the manuscript contains significant new results and it reflects sufficiently high scientific standards to warrant its eventual publication in Communications Earth & Environment Journal. In addition, the manuscript is well-written with the maximum conciseness compatible with accuracy
and clarity.

For the reasons pointed out above, I am glad to recommend this manuscript for publication in Communications Earth & Environment after minor revision due to the following technical issues that should be addressed in a new version of
this work.

1) RELAB has been used but I think no link to the actual database or references have been provided. For example:
http://www.planetary.brown.edu/relab/

Strength of mineral absorption features in the transmitted component of near-infrared reflected light - First results from RELAB https://ui.adsabs.harvard.edu/abs/1983JGR....88.9534P/abstract

Pieters C. M., Hiroi T., 2004, in Mackwell S., Stansbery E., eds, Lunar and Planetary Inst. Technical Report Vol. 35, Lunar and Planetary Science Conference, abstract no. 1720
RELAB (Reflectance Experiment Laboratory): A NASA Multiuser Spectroscopy Facility
https://ui.adsabs.harvard.edu/abs/2004LPI....35.1720P/abstract

Milliken R. E., Hiroi T., Patterson W., Contribution number 1903, 47th Lunar and Planetary Science Conference, held March 21-25, 2016 at TheWoodlands, Texas. LPI Contribution No.pp.2058 The NASA Reflectance Experiment Laboratory (RELAB) Facility: Past, Present, and Future
https://ui.adsabs.harvard.edu/abs/2016LPI....47.2058M/abstract

Did the authors compare just with actual lunar rocks or with lunar meteorites found on Earth as well? If lunar meteorites were not used, why?

2) Why just one Solar analog to do the spectral processing?

3) Did the authors check other light-curve analysis tools such as Python lightkurve?

https://docs.lightkurve.org/

Are the results consistent?

JPL's Horizons indicates:

Result based on less than full coverage, so that the period may be wrong by 30 percent or so.
Published Reference List:
[Reddy, V.; Kuhn, O.; Thirouin, A.; Conrad, A.; et al (2017). DPS 49, 204.07.

http://lbtonews.blogspot.com/2017/10/earths-new-traveling-buddy-is.html?spref=fb]

4) The dynamical analysis carried out by the authors involves the use of numerical simulations to study the short-term orbital evolution of Earth's quasi-satellite Kamo`oalewa and the authors have used the old DE430/431 planetary ephemeris to
perform such study (a retrieval date of January 6, 2021 is given). JPL's Horizons ephemeris system has been updated (late April-early May) to replace the DE430/431 planetary ephemeris, used since 2013, with the new DE440/441 solution. The new
DE440/441 general-purpose planetary solution includes seven additional years of ground and space-based astrometric data, data calibrations, and dynamical model improvements. Also check for any new values of the planetary masses (including the Moon and perhaps other objects). Additional details can be found here:

The JPL Planetary and Lunar Ephemerides DE440 and DE441
https://ui.adsabs.harvard.edu/abs/2021AJ....161..105P/abstract

For this reason, I encourage the authors to repeat their calculations using the new DE430/431 planetary ephemeris and to include the corresponding analysis of the new results obtained in the revised version of their manuscript (the latest orbit determination for this object was released on 2021-Apr-14). Such a modification will benefit the robustness and reliability of the results presented by the authors regarding a possible lunar origin of this small body.
In addition, I would also like to see a brief discussion in terms of clone orbits and probability (not just the nominal orbit). How many past close encounters with the Moon are predicted by the simulations? How close were such encounters? Are past collisions with the Moon possible? Histograms may help the reader to realize the statistical significance of the results.

5) Is this an extended rewrite of the DPS contribution of 2017 that is not even cited in the manuscript?

Ground-based Characterization of Earth Quasi Satellite (469219) 2016 HO3
https://ui.adsabs.harvard.edu/abs/2017DPS....4920407R/abstract

Why is the DPS contribution not cited?

6) 2020 CD3 has a recent new reference:

Precovery Observations Confirm the Capture Time of Asteroid 2020 CD3 as Earth's Minimoon
https://iopscience.iop.org/article/10.3847/2041-8213/abf836/meta

7) Kamo`oalewa may have related known objects:

Using Mars co-orbitals to estimate the importance of rotation-induced YORP break-up events in Earth co-orbital space
https://ui.adsabs.harvard.edu/abs/2021MNRAS.501.6007D/abstract

8) The authors indicate "...exhibiting intermittent transitions between horseshoe and quasi-satellite motion..." This corresponds to:

QS-HS dynamical class:

horseshoe-retrograde satellite orbit transitions and librations.

Namouni F., 1999, Icarus, 137, 293

Secular Interactions of Coorbiting Objects
https://ui.adsabs.harvard.edu/abs/1999Icar..137..293N/abstract

9) The references for Python are:

Python2
```
@book{van1995python,
title={Python reference manual},
author={Van Rossum, Guido and Drake Jr, Fred L},
year={1995},
publisher={Centrum voor Wiskunde en Informatica Amsterdam}
}
```

Python3
```
@book{10.5555/1593511,
author = {Van Rossum, Guido and Drake, Fred L.},
title = {Python 3 Reference Manual},
year = {2009},
isbn = {1441412697},
publisher = {CreateSpace},
address = {Scotts Valley, CA}
}
```

The authors may have used Python 3 not 2. Indicate (links and references) the Python packages used to obtain the results presented in the manuscript.

10) Fig. 1. Please, indicate the reference used to perform the conversion.

Reviewer #2 (Remarks to the Author):

Review by Paul G. Lucey of the manuscript by Sharkey et al. entitled: Characterizing Earth Quasi-Satellite (469219) 2016 HO3 Kamo`oalewa

This is an extremely interesting paper that describes the spectral properties of quasi-satellite of the Earth, the first such work to do so. The authors present several hypotheses for the origin of this object, and argue that an ultimately lunar origin is most consistent with their observations.

I agree with this intepretation, but the argument could be strengthened in several ways.

First, the there should be a plot or histogram of the distribution of spectral slopes of the NEO population, and the slope value of the object for comparison, to support the claim that this object is not consistent with a NEO. Some similar plot should be provided to show that metal would either not work, or some data-driven way to show metal is implausible. Right now these two point are more assertions. The existing plots show examples, but with single spectra is not possible to assess if these are representative of their respective ranges of spectral behavior.

The comparison with the Apollo 11 soil somewhat uncuts the argument that lunar is a good origin simply because the composition of that soil is very extreme. It contains over 15 wt.% ilmenite, is just about the darkest material on the Moon, and the source ilmenite-rich rock covers at most a few percent of the lunar surface. A casual lunar spectroscopist could dismiss the argument on that basis, that the proposed analog is so rare, it is not a plausible hypothesis. But I infer that the authors' argument is that, because this object is so red, lunar-style space weathering should be considered. I agree with that. I would suggest the author's reference Wentworth et al. 1999 who showed that rock surfaces exposed to space on the Moon for a few million years were spectrally red and contain a lot of submicroscopic iron. More recently, Lin et al. 2020 showed near-IR spectra of a lunar boulder on the surface of the Moon and it too was spectrally very red (but not very dark). So, a regolith is not needed to exhibit extreme reddening. The authors should directly compare the slopes of the Wentworth and Lin spectra to improve the argument, but I think these papers support the hypothesis better than the 10084 match.

Some line by line comments:

44 "comprised" is used like "include." "... could comprise lunar material."

59 "3)" seems like two things.

67 There is a nice description of quasi-satellites farther down in the manuscript, it really belongs up here to inform the non-specialist reader.

68 "This class of objects has only recently been studied" Not quite getting this. Meaning they were discovered in 2004 but not really studied until now?

114-117 Show the distribution of slopes here, and the uniqueness of this object.

127 Confused here. The previous sentence discuss the change in slope with phase, but this seems to be giving and absolute value, not a delta.

130-131 "not blue as would be expected from grain size effects alone" This is relative to what. I think I see the point, but I'm not sure.

140 This doesn't seem like a compelling argument, just an example that maybe just happened not to

work.

144 Gaffey is not really a good primary reference for this, maybe Fisher and Pieters, 1996.

145-146 Be specific about what samples were examined and references exactly. The "19" makes me suspect this is the LSCC data base and these include highland samples. I would not tie yourself to the maria, they cover only 17% of the lunar surface, and the Apollo 11 basalts are a small fraction of that.

151-153 Show, not just tell.

157 "Adopting these values" the range came from the .06 and 0.16? I think that's clear, but not totally.

Fisher, E. and CM., Pieters (1996), JGR,
Vol. 101, N°E1, 2225-34.

Lin H, He Z, Yang W, Lin Y, Xu R, Zhang C, Zhu MH, Chang R, Zhang J, Li C, Lin H. Olivine-norite rock detected by the lunar rover Yutu-2 likely crystallized from the SPA-impact melt pool. National Science Review. 2020 May 1;7(5):913-20.

Wentworth SJ, Keller LP, McKAY DS, Morris RV. Space weathering on the Moon: Patina on Apollo 17 samples 75075 and 76015. Meteoritics & Planetary Science. 1999 Jul;34(4):593-603.

REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

Journal: Communications Earth & Environment

Manuscript #: COMMSENV-21-0303-T

Title: Characterizing Earth Quasi-Satellite (469219) 2016 HO3 Kamo`oalewa

Authors: Benjamin N. L. Sharkey, Vishnu Reddy, Renu Malhotra, Audrey Thirouin, Olga Kuhn, Albert Conrad, Barry Rothberg, Juan A. Sanchez, David Thompson, Christian Veillet

Based on the analysis of a reflectance spectrum of Earth's quasi-satellite 469219 Kamo`oalewa (2016 HO3), the authors of this manuscript carry out the fundamental and very important task of physically characterizing such an interesting asteroid. Few Earth co-orbital asteroids have been observed spectroscopically as they are rather challenging targets in terms of brightness and visibility windows. After applying a solid, sound, and reliable methodology, the authors arrived to a novel, original, and groundbreaking result that entertains the possibility of an origin of Kamo`oalewa as lunar ejecta. Lunar craters are well understood and lunar meteorites are also well documented. The tentative result presented in this manuscript links both subjects, unveiling a possible dynamical pathway from the surface of the Moon to the surface of our
planet. If confirmed, it would be a truly revolutionary result of great interest for the entire scientific community.

According to the authors, the reflectance spectrum of Kamo`oalewa shows features consistent with a silicate-based chemical composition of its surface involving a significant level of reddening that is higher than the typical one among asteroids in the inner solar system. Then the authors further elaborate on this, finding that the best matching corresponds to that of the spectra of lunar-like silicates, which leads them to infer a possible lunar origin. In summary, I believe the manuscript contains significant new results and it reflects sufficiently high scientific standards to warrant its eventual publication in Communications Earth & Environment Journal. In addition, the manuscript is well-written with the maximum conciseness compatible with accuracy and clarity.

For the reasons pointed out above, I am glad to recommend this manuscript for publication in Communications Earth & Environment after minor revision due to the following technical issues that should be addressed in a new version of this work.

1) RELAB has been used but I think no link to the actual database or references have been provided. For example:
http://www.planetary.brown.edu/relab/

Strength of mineral absorption features in the transmitted component of near-infrared reflected light - First results from RELAB
https://ui.adsabs.harvard.edu/abs/1983JGR....88.9534P/abstract

Pieters C. M., Hiroi T., 2004, in Mackwell S., Stansbery E., eds, Lunar and Planetary Inst. Technical Report Vol. 35, Lunar and Planetary Science Conference, abstract no. 1720
RELAB (Reflectance Experiment Laboratory): A NASA Multiuser Spectroscopy Facility
https://ui.adsabs.harvard.edu/abs/2004LPI....35.1720P/abstract

Milliken R. E., Hiroi T., Patterson W., Contribution number 1903, 47th Lunar and Planetary Science Conference, held March 21-25, 2016 at TheWoodlands, Texas. LPI Contribution No.pp.2058 The NASA Reflectance Experiment Laboratory (RELAB) Facility: Past, Present, and Future
https://ui.adsabs.harvard.edu/abs/2016LPI....47.2058M/abstract

Response: We thank the reviewer for pointing to these necessary citations, we have included these in addition to the primary citation for lunar sample data given in Taylor et al. (2001).

Did the authors compare just with actual lunar rocks or with lunar meteorites found on Earth as well? If lunar meteorites were not used, why?

Response: We thank the reviewer for the suggestion and we did indeed discuss the possibility of using lunar meteorites in addition to the Apollo samples. However, we concluded that by focusing on comparisons to Apollo mission samples, we are attempting to avoid concerns about terrestrial weathering of lunar meteorites (which are all finds rather than falls), which can cause significant spectral effects due to terrestrial alteration products. In addition, there is no single dedicated database of all lunar meteorites which can be accessed easily. Since the LSSC data set provides a wide variety of materials, we aim to provide comparisons to a very well characterized suite of primary samples.

2) Why just one Solar analog to do the spectral processing?

Response: We thank the reviewer for the comment and are happy to clarify about the solar analogs. We note that several different solar analogs were used (HIP 52192, SAO120107, GSPC 330-E) in the processing of the spectral data and also the infrared colors. We apologize for not making this clear in the paper but it is in the methods section.

3) Did the authors check other light-curve analysis tools such as Python lightkurve?

https://docs.lightkurve.org/

Are the results consistent?

Response: We thank the reviewer for the suggestion. Our main technique to search for periodicity is the Lomb-Scargle method because it takes into account that we are working with irregularly spaced data. But, we always double-check our results with other periodicity search techniques such as the Phase Dispersion Minimization (PDM) which was developed by Harris et al. (1989), and the CLEAN technique by Foster et al. (1995). CLEAN, PDM, and Lomb-Scargle are the main periodicity search techniques used for small bodies and have been proven for decades. In the case of 2016 HO3, all periodicity search tools are giving a consistent result, and thus we are confident with our periodogram in Figure 4. Also, it is important to point out that Tholen et al. 2016 confirmed our period estimate with an independent dataset from the LDT+LBT.

We did not use the lightkurve tool which was mainly developed for exoplanet transits using Kepler, K2, and TESS data. Several small body papers using K2 and TESS data are not using this tool either (Pal et al. 2020, Marton et al. 2020, Szabo et al. 2020).

JPL's Horizons indicates:

Result based on less than full coverage, so that the period may be wrong by 30 percent or so.
Published Reference List:
[Reddy, V.; Kuhn, O.; Thirouin, A.; Conrad, A.; et al (2017). DPS 49, 204.07.
http://lbtonews.blogspot.com/2017/10/earths-new-traveling-buddy-is.html?spref=fb]

Response: We thank the reviewer for the comment and would like to clarify a few things below. JPL's Horizons is extracting this information from the Lightcurve Database (Warner et al. 2009). Based on a personal evaluation, Warner et al. give a code (U code from 0 to 3) to each published lightcurve. As mentioned in Section 4.1.2 of http://www.minorplanet.info/datazips/LCDB_readme.txt : "The U code provides our assessment of the quality of the period solution, not necessarily of the data per se." The period of a lightcurve with a U code of 2 is by default considered to be uncertain by 30%. Based on our DPS presentation in 2017 and the LBT blog, Warner et al. estimated that our lightcurve has a U code of 2. The referee will appreciate that the details of the Warner et al. assessment are not discussed in great detail in the online documentation and that the U code was given based on a visual inspection from a blog as our data, as well as analysis, are not published yet. We consider that our rotational period estimate and associated error bar are discussed and justified in our paper.

4) The dynamical analysis carried out by the authors involves the use of numerical simulations to study the short-term orbital evolution of Earth's quasi-satellite Kamo`oalewa and the authors have used the old DE430/431 planetary ephemeris to perform such study (a retrieval date of January 6, 2021 is given). JPL's Horizons ephemeris system has been updated (late April-early May) to replace the DE430/431 planetary ephemeris, used since 2013, with the new DE440/441 solution. The new

DE440/441 general-purpose planetary solution includes seven additional years of ground and space-based astrometric data, data calibrations, and dynamical model improvements. Also check for any new values of the planetary masses (including the Moon and perhaps other objects). Additional details can be found here:

The JPL Planetary and Lunar Ephemerides DE440 and DE441
https://ui.adsabs.harvard.edu/abs/2021AJ....161..105P/abstract

For this reason, I encourage the authors to repeat their calculations using the new DE430/431 planetary ephemeris and to include the corresponding analysis of the new results obtained in the revised version of their manuscript (the latest orbit determination for this object was released on 2021-Apr-14). Such a modification will benefit the robustness and reliability of the results presented by the authors regarding a possible lunar origin of this small body.

Response: We thank the reviewer for the comment and in the revised manuscript, we have updated Figure 3 with JPL's new DE440/441 planetary ephemeris (and cited Park et al. 2021). We would like to note that there is no change in results.

In addition, I would also like to see a brief discussion in terms of clone orbits and probability (not just the nominal orbit). How many past close encounters with the Moon are predicted by the simulations? How close were such encounters? Are past collisions with the Moon possible? Histograms may help the reader to realize the statistical significance of the results.

Response: We thank the reviewer for the suggestion and would like to note that calculations of clone orbits and estimates of past close encounters or collisions with the Moon require large scale simulations that are beyond the scope of the present work. As noted in our paper, some calculations with sampling of clone orbits have been published by other authors (de la Fuente Marcos & de la Fuente Marcos 2016; Dermawan 2019; Rezky & Soegiartini 2020); these authors did not consider lunar origin. Regarding past close encounters or collisions with the Moon, we are carrying out numerical simulations for such a study and results will be reported in a future publication. For the scope of the present work, we have noted in this paper that the low close approach velocity of Kamo’oalewa to Earth-Moon supports an origin within the Earth-Moon system.

5) Is this an extended rewrite of the DPS contribution of 2017 that is not even cited in the manuscript?

Ground-based Characterization of Earth Quasi Satellite (469219) 2016 HO3
https://ui.adsabs.harvard.edu/abs/2017DPS....4920407R/abstract

Why is the DPS contribution not cited?

Response: We thank the reviewer for the comment and we apologize for this oversight. The DPS abstract presented preliminary results based on a subset of the data collected here (none of the infrared data was taken in 2017) and only minor preliminary analysis had been performed for that abstract. Our analysis here is substantially more involved and is based on a larger data set, which is presented in its entirety in this manuscript for the first time.

6) 2020 CD3 has a recent new reference:

Precovery Observations Confirm the Capture Time of Asteroid 2020 CD3 as Earth's Minimoon
https://iopscience.iop.org/article/10.3847/2041-8213/abf836/meta

Response: We thank the reviewer for noting this reference, which we now include in our discussion of 2020 CD3.

7) Kamo`oalewa may have related known objects:

Using Mars co-orbitals to estimate the importance of rotation-induced YORP break-up events in Earth co-orbital space
https://ui.adsabs.harvard.edu/abs/2021MNRAS.501.6007D/abstract

Response: We thank the reviewer for noting this reference and have added a citation to this paper, and a sentence about potential related objects.

8) The authors indicate "...exhibiting intermittent transitions between horseshoe and quasi-satellite motion..." This corresponds to:

QS-HS dynamical class:

horseshoe-retrograde satellite orbit transitions and librations.

Namouni F., 1999, Icarus, 137, 293

Secular Interactions of Coorbiting Objects
https://ui.adsabs.harvard.edu/abs/1999Icar..137..293N/abstract

Response: We thank the reviewer for the suggestion and have added a sentence about this and a citation to this paper.

9) The references for Python are:

Python2
@book{van1995python,
title={Python reference manual},
author={Van Rossum, Guido and Drake Jr, Fred L},
year={1995},
publisher={Centrum voor Wiskunde en Informatica Amsterdam}
}

Python3
@book{10.5555/1593511,
author = {Van Rossum, Guido and Drake, Fred L.},
title = {Python 3 Reference Manual},
year = {2009},
isbn = {1441412697},
publisher = {CreateSpace},
address = {Scotts Valley, CA}
}

The authors may have used Python 3 not 2. Indicate (links and references) the Python packages used to obtain the results presented in the manuscript.

Response: We thank the reviewer for pointing out our need for software citations. We have included citations to python 3, as well as the astropy collaboration and the photutils package that we utilized for our analysis.

10) Fig. 1. Please, indicate the reference used to perform the conversion.

Response: We thank the reviewer for the comment. The formula to convert the absolute magnitude to diameter can be found in Pravec & Harris, 2007 (Icarus, 190, 250), equation A.5. This citation is now included in the caption for figure 1.

Reviewer #2 (Remarks to the Author):

This is an extremely interesting paper that describes the spectral properties of quasi-satellite of the Earth, the first such work to do so. The authors present several hypotheses for the origin of this object, and argue that an ultimately lunar origin is most consistent with their observations.

I agree with this intepretation, but the argument could be strengthened in several ways.

First, the there should be a plot or histogram of the distribution of spectral slopes of the NEO population, and the slope value of the object for comparison, to support the claim that this object is not consistent with a NEO. Some similar plot should be provided to show that metal would either not work, or some data-driven way to show metal is implausible. Right now these two point are more assertions. The existing plots show examples, but with single spectra is not possible to assess if these are representative of their respective ranges of spectral behavior.

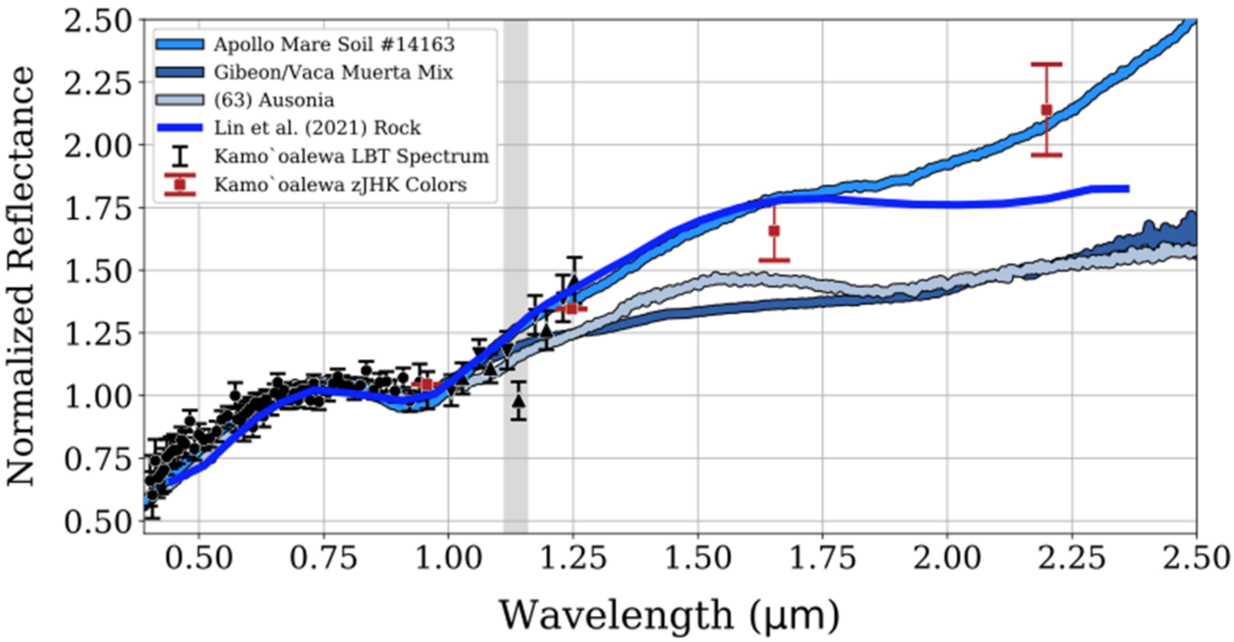
Response: We thank the reviewer for this excellent suggestion. We have included a histogram in Figure 3 as suggested by the reviewer here. By looking at 470 S- and L-type asteroids from Binzel et al. (2019), the most comprehensive NIR spectral survey of NEOs to date, we find that Kamo`oalewa has a unique spectral slope when compared to 99.8% of this sample. Other asteroids, mainly D- and A-type asteroids, can have similar spectral slopes to what we measured here, but such asteroids have different 1.0 micron band properties (either no silicate bands for D-types, or very deep bands at shifted wavelengths for olivine-rich A-types) compared to Kamo`oalewa. We thank the reviewer for this suggestion for strengthening the argument.

The comparison with the Apollo 11 soil somewhat uncuts the argument that lunar is a good origin simply because the composition of that soil is very extreme. It contains over 15 wt.% ilmenite, is just about the darkest material on the Moon, and the source ilmenite-rich rock covers at most a few percent of the lunar surface. A casual lunar spectroscopist could dismiss the argument on that basis, that the proposed analog is so rare, it is not a plausible hypothesis. But I infer that the authors' argument is that, because this object is so red, lunar-style space weathering should be considered. I agree with that. I would suggest the author's reference Wentworth et al. 1999 who showed that rock surfaces exposed to space on the Moon for a few million years were spectrally red and contain a lot of submicroscopic iron. More recently, Lin et al. 2020 showed near-IR spectra of a lunar boulder on the surface of the Moon and it too was spectrally very red (but not very dark).
So, a regolith is not needed to exhibit extreme reddening. The authors should directly compare the slopes of the Wentworth and Lin spectra to improve the argument, but I think these papers support the hypothesis better than the 10084 match.

Response: We thank the reviewer for providing additional context here. We examined all of the soils present in the LSSC database. Generally, we find that the best matches to the quasi-satellite are among the mare soils, but we interpret this mainly as a selection effect due to the wide variety of spectral slopes present among them. We still think that soil sample 10084 is useful as it traces very closely to the asteroid spectrum, but other plausible matches include 14163, 79221, 71501, and 70181.

In our revised submission, we have opted to plot sample 14163 in an attempt to address the concerns about the rarity of the Apollo 11 materials raised here. The main properties we believe are noteworthy are that darker lunar materials generally appear to better match the visible portion of the asteroid spectrum, but many samples appear to match the infrared slope. We are in agreement with this larger point that the reviewer raises - we do not believe our conclusions rest on showing a single match to a single lunar sample, and we are generally cautious about overinterpreting matches without higher resolution spectra that would allow baseline chemical analysis of silicates from formal band parameters.

The Wentworth data show relatively neutral spectra that don't appear to be a good match for our case. The Lin paper showing the spectrum of the rock from Chang'e 4 shows a close match to our observed spectrum, except for 1.75-2.5 microns where the rock spectrum rolls over to neutral colors. While we are unsure of how to access the data using the mission's archive tool (as it is not prepared in English), we have at least verified this by digitizing the rock spectrum from the figure in the paper, and include an example for the convenience of the reviewer here. We have included a statement that Lin et al. (2021) show that the spectrum of a lunar boulder can also exhibit reddening consistent with the general slope we observe.



Some line by line comments:

44 "comprised" is used like "include." "... could comprise lunar material."
Response: We have corrected this.

59 "3)" seems like two things.

Response: While physically these imply vastly different histories, from the perspective of orbital modeling they are very similar and can be difficult to distinguish, and therefore we think it is reasonable to keep them grouped here.

67 There is a nice description of quasi-satellites farther down in the manuscript, it really belongs up here to inform the non-specialist reader.

We agree with this suggestion to improve the manuscript's readability. We have reorganized the text, moving the text describing general properties of quasi-satellites to the introductory paragraph as suggested.

68 "This class of objects has only recently been studied" Not quite getting this. Meaning they were discovered in 2004 but not really studied until now?

Response: We only mean to imply that, relative to other near-Earth populations, the discovery and subsequent study of quasi-satellites is relatively recent. We have revised the phrasing of the text to clarify.

114-117 Show the distribution of slopes here, and the uniqueness of this object.

127 Confused here. The previous sentence discuss the change in slope with phase, but this seems to be giving and absolute value, not a delta.

Response: We thank the reviewer for the comment. With this discussion, we mean to point out that phase corrections to the spectrum are limited to <<30%/micron, which itself is much smaller than the slope differences between Kamo`oalewa and typical S-type asteroids.

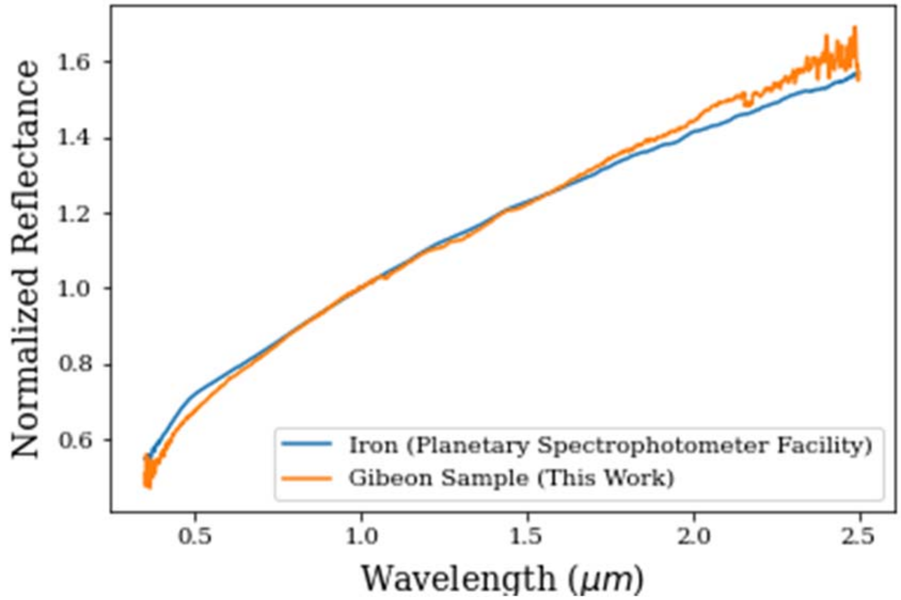
130-131 "not blue as would be expected from grain size effects alone" This is relative to what. I think I see the point, but I'm not sure.

Response: We are comparing to S-types with neutral reflectances in this case, and have attempted to clarify in text.

140 This doesn't seem like a compelling argument, just an example that maybe just happened not to work.

Response: We thank the reviewer for pointing this out, as we did not fully explain this curve in the original text. We hope that the amended text clarifies our reasoning, and we provide further discussion here.
While it is true that it provides only a single example which does not work (and cannot on its own rule out exotic metals as a reddening agent), Gibeon itself has the reddest known spectral slope among iron meteorites we have studied in the lab for another project looking at Psyche regolith analogs (Cantillo et al. 2021). Spectral slope decreases as nickel is added, so Gibeon's spectral slope is pretty similar to something that is mostly iron. This example does show that adding enough silicate material to approximate the 1.0 micron absorption significantly reduces the red spectral slope of the Gibeon sample. In other words, we need to add an additional reddening agent beyond the metal to make it match with our target. We are limited to the available inventory of metallic meteorites with this approach, but such approaches, for example, have been successfully applied to model metal rich asteroids such as Psyche by our group (Cantillo et al. 2021). Essentially, Gibeon provides the reddest spectrum amongst metallic meteorite samples, and adding silicates to fit the 1.0 micron band reduces the spectral slope in a way that makes it a poor match to Kamo`oalewa.

https://ui.adsabs.harvard.edu/abs/2021PSJ.....2...95C/abstract



We include here a snapshot of the Gibeon spectrum we are using in comparison with an iron sample measured by the University of Winnipeg's Planetary Spectrophotometer Facility (link below).

https://psf.uwinnipeg.ca/Sample_Database/

144 Gaffey is not really a good primary reference for this, maybe Fisher and Pieters, 1996.

Response: We thank the reviewer for the suggestion and have included Fischer and Pieters (1996) as the reference.

145-146 Be specific about what samples were examined and references exactly. The "19" makes me suspect this is the LSCC data base and these include highland samples. I would not tie yourself to the maria, they cover only 17% of the lunar surface, and the Apollo 11 basalts are a small fraction of that.

Response: See our discussion above.

151-153 Show, not just tell.

Response: We hope Figure 3 accomplishes this.

157 "Adopting these values" the range came from the .06 and 0.16? I think that's clear, but not totally.

Response: The reviewer’s interpretation is correct, we have adjusted the text to clarify and to update the albedo with the value for sample 14163.

Fisher, E. and CM., Pieters (1996), JGR,
Vol. 101, N°E1, 2225-34.

Lin H, He Z, Yang W, Lin Y, Xu R, Zhang C, Zhu MH, Chang R, Zhang J, Li C, Lin H. Olivine-norite rock detected by the lunar rover Yutu-2 likely crystallized from the SPA-impact melt pool. National Science Review. 2020 May 1;7(5):913-20.

Wentworth SJ, Keller LP, McKAY DS, Morris RV. Space weathering on the Moon: Patina on Apollo 17 samples 75075 and 76015. Meteoritics & Planetary Science. 1999 Jul;34(4):593-603.

Response: We have included the Fischer reference:
https://ui.adsabs.harvard.edu/abs/1996JGR...101.2225F/abstract

As well as the Lin et al. reference.

9th Sep 21

Dear Mr Sharkey,

Your manuscript titled "Characterizing Earth Quasi-Satellite (469219) 2016 HO3 Kamo`oalewa" has now been seen by our reviewers, whose comments appear below. In light of their advice I am delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment under the open access CC BY license (Creative Commons Attribution v4.0 International License).

We therefore invite you to revise your paper one last time to address the remaining concerns of our reviewers. At the same time we ask that you edit your manuscript to comply with our format requirements and to maximise the accessibility and therefore the impact of your work.

EDITORIAL REQUESTS:

Please review our specific editorial comments and requests regarding your manuscript in the attached "Editorial Requests Table". Please outline your response to each request in the right hand column. Please upload the completed table with your manuscript files.

If you have any questions or concerns about any of our requests, please do not hesitate to contact me.

SUBMISSION INFORMATION:

In order to accept your paper, we require the files listed at the end of the Editorial Requests Table; the list of required files is also available at https://www.nature.com/documents/commsj-file-checklist.pdf .

OPEN ACCESS:

Communications Earth & Environment is a fully open access journal. Articles are made freely accessible on publication under a CC BY license (Creative Commons Attribution 4.0 International License). This license allows maximum dissemination and re-use of open access materials and is preferred by many research funding bodies.

For further information about article processing charges, open access funding, and advice and support from Nature Research, please visit https://www.nature.com/commsenv/about/open-access

At acceptance, you will be provided with instructions for completing this CC BY license on behalf of all authors. This grants us the necessary permissions to publish your paper. Additionally, you will be asked to declare that all required third party permissions have been obtained, and to provide billing information in order to pay the article-processing charge (APC). Please note that that we will not be able to move forward without having first received your payment information and third-party declarations and therefore we ask that you please have this information ready when submitting the final version of your manuscript.

Please use the following link to submit the above items:
[link redacted]
** This url links to your confidential home page and associated information about manuscripts you may have submitted or be reviewing for us. If you wish to forward this email to co-authors, please delete the link to your homepage first **

We hope to hear from you within two weeks; please let us know if you need more time.

Best regards,

Joe Aslin

Associate Editor,
Communications Earth & Environment
https://www.nature.com/commsenv/
Twitter: @CommsEarth

REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

Journal: Communications Earth & Environment

Manuscript #: COMMSENV-21-0303A

Title: Characterizing Earth Quasi-Satellite (469219) 2016 HO3 Kamo`oalewa

Authors: Benjamin N. L. Sharkey, Vishnu Reddy, Renu Malhotra, Audrey Thirouin,
Olga Kuhn, Albert Conrad, Barry Rothberg, Juan A. Sanchez, David
Thompson, Christian Veillet

The revised version of this manuscript has addressed most shortcomings identified in my first report. There are however a number of minor issues that should be fixed before the manuscript can be accepted. The list of issues to be fixed follows. Given the nature of most of them, I believe that I do not have to see the revised manuscript again: the editor may confirm directly that the changes have been made and avoid an additional round of review.

Minor issues
============

0) Use of Fig./Figs. or Figure/Figures throughout the manuscript.
Which one is right?

1) Add table with latest orbital properties of Kamo`oalewa.

2) Line 1. Subscript, 2016~HO$_{3}$.

3) Line 38. Missing "a" or "the"?

4) Line 49. Also because they are relatively easy to access from Earth.
See, for example:

Simulation of global GM estimate of Asteroid (469219) 2016 HO3 for
China's future asteroid mission
https://ui.adsabs.harvard.edu/abs/2019EPSC...13.1485J/abstract

Dynamics and control of proximity operations for asteroid exploration
mission
https://ui.adsabs.harvard.edu/abs/2019SSPMA..49h4508L/abstract

Near-Earth Asteroid Characterization and Observation (NEACO) Mission
to Asteroid (469219) 2016 HO3
https://ui.adsabs.harvard.edu/abs/2019JSpRo..56.1121V/abstract

In fact, the results in this manuscript could be of some help to
the missions described above.

5) Line 54. "...the most stable known..."

6) Line 67. Subscript, 2016~HO$_{3}$.

7) Line 68. "...of the five known..."

8) The standard designation for the semi-major axis in celestial mechanics
is "a" (in LaTeX).

9) Line 74. Subscript, 2004~GU$_{9}$.

10) Line 80. Subscript, 2020~CD$_{3}$.

11) Line 86. Reference should go after "modes".

12) Line 167. It reads strange. Anything wrong here?

13) Line 218. Also:

Orbit Determination of the Asteroid (469219) Kamo\`{}oalewa and Its Error

Analysis
https://ui.adsabs.harvard.edu/abs/2021AcASn..62...16T/abstract

Study of the Dynamics of the Asteroid Kamo`Oalewa
https://ui.adsabs.harvard.edu/abs/2021RuPhJ..63.1989G/abstract

The strength is discussed here (see also Fig. 2, right-hand side panel):

Critical spin periods of sub-km-sized cohesive rubble-pile asteroids: dependences on material parameters
https://ui.adsabs.harvard.edu/abs/2021MNRAS.502.5277H/abstract

14) Line 228. Remove extra comma.

15) Line 236. "De la..."

16) Line 261. Something might be wrong here. SAO 120107 seems to be a giant star, G5III, not a solar analog, G2V:

https://simbad.u-strasbg.fr/simbad/sim-id?Ident=SA+120107&NbIdent=1&Radius=2&Radius.unit=arcmin&submit=submit+id

17) Line 270. The name of the star cited is incorrect. See:

https://simbad.u-strasbg.fr/simbad/sim-id?Ident=GSPC+P330-E&NbIdent=1&Radius=2&Radius.unit=arcmin&submit=submit+id

18) Line 322. Remove extra dot.

19) Figure 3. Missing bin size discussion. Is it statistically motivated? See:

https://numpy.org/doc/stable/reference/generated/numpy.histogram_bin_edges.html#numpy.histogram_bin_edges

20) Figure 4. The libration about 0 deg in Figure 4, bottom panel is not discussed in the text of the manuscript as it should. On the other hand, the distance Earth-asteroid is discussed in the text (lines 201 to 221) but it is not shown in Figure 4.

21) Line 415. The last name of one of the authors is incorrect, but in line 420 the same last name is correct.

22) Lines 438, 457, and 524. Isn't it the same journal?

23) Line 447. Something wrong with MNRAS.

24) Line 505. Missing space.

25) Line 515. Missing URL or publisher?

26) Line 517. Missing space.

Reviewer #2 (Remarks to the Author):

The manuscript has been revised to my satisfaction and I have no further comments.

REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

Journal: Communications Earth & Environment

Manuscript #: COMMSENV-21-0303A

Title: Characterizing Earth Quasi-Satellite (469219) 2016 HO3 Kamo`oalewa

Authors: Benjamin N. L. Sharkey, Vishnu Reddy, Renu Malhotra, Audrey Thirouin, Olga Kuhn, Albert Conrad, Barry Rothberg, Juan A. Sanchez, David Thompson, Christian Veillet

The revised version of this manuscript has addressed most shortcomings identified in my first report. There are however a number of minor issues that should be fixed before the manuscript can be accepted. The list of issues to be fixed follows. Given the nature of most of them, I believe that I do not have to see the revised manuscript again: the editor may confirm directly that the changes have been made and avoid an additional round of review.

Minor issues
============

0) Use of Fig./Figs. or Figure/Figures throughout the manuscript. Which one is right?

1) Add table with latest orbital properties of Kamo`oalewa.

We thank the reviewer for the suggestion and we are in principle not opposed to this, however the relevant details (semimajor axis, eccentricity, inclination) are provided to the reader in-text in the second sentence of the introductory paragraph and we feel that a separate table for this information might be excessive. In addition, this information is also publicly available at the source (JPL-Horizons, cited in the paper).

2) Line 1. Subscript, 2016~HO$_{3}$. We have made the suggested correction.

3) Line 38. Missing "a" or "the"? We thank the reviewer for this suggestion, and note that this portion of the text was in the cover-letter summary for the previous draft, which has now been replaced with the combined abstract paragraph.

4) Line 49. Also because they are relatively easy to access from Earth. See, for example:

Simulation of global GM estimate of Asteroid (469219) 2016 HO3 for China's future asteroid mission
https://ui.adsabs.harvard.edu/abs/2019EPSC...13.1485J/abstract

Dynamics and control of proximity operations for asteroid exploration
mission
https://ui.adsabs.harvard.edu/abs/2019SSPMA..49h4508L/abstract

Near-Earth Asteroid Characterization and Observation (NEACO) Mission
to Asteroid (469219) 2016 HO3
https://ui.adsabs.harvard.edu/abs/2019JSpRo..56.1121V/abstract

In fact, the results in this manuscript could be of some help to
the missions described above.

We have included this citations in the introductory paragraph as suggested by the reviewer.

5) Line 54. "...the most stable known..." We have made this change as suggested by the reviewer. .

6) Line 67. Subscript, 2016~HO$_{3}$.We have made this change as suggested by the reviewer..

7) Line 68. "...of the five known..." We have made this change as suggested by the reviewer..

8) The standard designation for the semi-major axis in celestial mechanics
is "a" (in LaTeX). Corrected, we no longer use any abbreviation here since it is used only twice.

9) Line 74. Subscript, 2004~GU$_{9}$. We have made this change as suggested by the reviewer..

10) Line 80. Subscript, 2020~CD$_{3}$. We have made this change as suggested by the reviewer.

11) Line 86. Reference should go after "modes". We have made this change as suggested by the reviewer.

12) Line 167. It reads strange. Anything wrong here? We have rephrased the statement, we agree with the reviewer and hope this addresses the issue.

13) Line 218. Also:

Orbit Determination of the Asteroid (469219) Kamo\`{}oalewa and Its Error
Analysis
https://ui.adsabs.harvard.edu/abs/2021AcASn..62...16T/abstract

Study of the Dynamics of the Asteroid Kamo`Oalewa
https://ui.adsabs.harvard.edu/abs/2021RuPhJ..63.1989G/abstract

The strength is discussed here (see also Fig. 2, right-hand side panel):

Critical spin periods of sub-km-sized cohesive rubble-pile asteroids: dependences on material parameters
https://ui.adsabs.harvard.edu/abs/2021MNRAS.502.5277H/abstract

The three references indicated above have been added in the final paragraph of the “Results and Discussion” section.

14) Line 228. Remove extra comma. We have made this change as suggested by the reviewer..

15) Line 236. "De la..." The capitalization of the authors names as listed in the cited paper is “de la,” and we believe it is best to use this for consistency.

16) Line 261. Something might be wrong here. SAO 120107 seems to be a giant star, G5III, not a solar analog, G2V:

https://simbad.u-strasbg.fr/simbad/sim-id?Ident=SAO+120107&NbIdent=1&Radius=2&Radius.unit=arcmin&submit=submit+id

We appreciate the reviewer’s question about this analog star. Since stellar classification is typically based on visible color indices, for infrared spectroscopy individual solar analogs must be observed separately to be vetted. Our group has extensively used this specific analog in the infrared.

17) Line 270. The name of the star cited is incorrect. See:

https://simbad.u-strasbg.fr/simbad/sim-id?Ident=GSPC+P330-E&NbIdent=1&Radius=2&Radius.unit=arcmin&submit=submit+id

We thank the reviewer for catching this typo, and have also added in a reference for this star’s suitability as a solar analog.

18) Line 322. Remove extra dot. We have made this change as suggested by the reviewer.

19) Figure 3. Missing bin size discussion. Is it statistically motivated? See:

https://numpy.org/doc/stable/reference/generated/numpy.histogram_bin_edges.html#numpy.histogram_bin_edges

We do not perform any analysis based on the binned data, which is shown simply with 50 equal-width bins. We now briefly note this in the caption for the figure. We only show this plot to illustrate the range of the slopes reported by Binzel et al. (2019).

20) Figure 4. The libration about 0 deg in Figure 4, bottom panel is not discussed in the text of the manuscript as it should. On the

other hand, the distance Earth-asteroid is discussed in the text
(lines 201 to 221) but it is not shown in Figure 4.

Additional discussion has been given in the text for Figure 4, and a third panel showing the geocentric distance to the asteroid has been added as requested.

21) Line 415. The last name of one of the authors is incorrect, but in
line 420 the same last name is correct. We have made this change as suggested by the reviewer..

22) Lines 438, 457, and 524. Isn't it the same journal? We have made this change as suggested by the reviewer.

23) Line 447. Something wrong with MNRAS. We have made this change as suggested by the reviewer.

24) Line 505. Missing space. We have made this change as suggested by the reviewer.

25) Line 515. Missing URL or publisher? We have made this change as suggested by the reviewer.

26) Line 517. Missing space. We have made this change as suggested by the reviewer.

Reviewer #2 (Remarks to the Author):

The manuscript has been revised to my satisfaction and I have no further comments.

Thank you.