

Hayabusa2 extended mission target asteroid 1998 KY26 is smaller and rotating faster than previously known

Corresponding Author: Dr Toni Santana-Ros

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)

The paper presents the results of a comprehensive study of the decameter-sized near-Earth asteroid (NEA) 1998 KY26. The authors estimated the rotation period and diameter of the asteroid, constructed models of convex and non-convex shapes and determined the pole direction, the optical albedo and taxonomic type, estimated the strength level, the amount of dust around the asteroid and the magnitude of non-gravitational acceleration. The results obtained are based on optical observations from 1998, 2020 and 2024, as well as radar observations carried out in 1998, which proves the effectiveness of the combined use of various Earth-based observation methods to determine the physical characteristics of small asteroids. It is worth noting the importance of the study, as it concerns the methods of remote determination of the physical and dynamic characteristics of the most common decameter NEAs, which pose a significant threat to human activity in the event of their collision with the Earth. Such objects can be observed only during rare close approaches to the Earth, so better knowledge of their orbits, understanding of their composition and structure will allow us to better assess the potential threat and possible consequences of a collision, increasing our planetary defense capabilities. In addition, the characteristics of asteroid 1998 KY26 obtained in the study can be used in planning the JAXA Hayabusa2# space mission to meet and explore this asteroid in July 2031.

The manuscript is well structured and presented in a clear language in accordance with the topic. The study is based on optical (photometric, astrometric and spectral) observations of asteroid 1998 KY26 conducted by the authors from May to November 2024 during its close approach to Earth.

The cornerstone of the study is the asteroid's rotation period obtained from photometric measurements on May 31, June 5 and June 12, which is about 5 minutes versus 11 minutes for Steven Ostro et al. in 1999. At the same time, the light curves from observations on June 2, 1998, May 19 and 21, 2024 give the same residuals for both periods of 5 and 11 minutes, and observations on October 27, November 1 and 7, 2024 are not given at all due to insufficient signal-to-noise ratio (SNR). The authors explain the obtained result by large (>60 deg) phase angles, at which more complex patterns on the light curves arise, caused by shading effects for non-convex shapes and angular characteristics for convex shapes. At the same time, the possibility is not considered, for example, that small decameter bodies have a more complex rotation than only around its principal axis (the so-called Tumblers), which could explain the change in the period at large phase angles.

Figure 1 clearly shows the poor representation of the June 2, 1998 observations by the red curve and the large errors in the photometric observations on June 12, 2024, potentially taking different approximations. I believe that it is necessary to supplement the graphs in Figure 1 with curves for an 11-minute period, and to provide in the text the values of the standard deviations of the presentation of photometric observations for periods of 5 and 11 minutes for each graph. It is also necessary to explain in more detail why at large phase angles we do not obtain a false value for the period, since subsequent results of the study (size, shape, etc.) obtained based on this new estimate of the period of 5 minutes. I propose to move the clarification in lines 443-445 (regarding the poor photometry on October 27, November 1 and 7) to the beginning of the Results section, since this information is necessary to present the overall picture of the data used. In lines 70-71, it is also necessary to add the astrometric observations of 2020, which were used in the study to determine the non-gravitational parameters.

I also propose to change (soften) the statement in lines 73-74 that the period obtained by Steven Ostro et al. in 1999 is "not correct". This is not entirely correct, since the finest-time-resolution photometric light curves of 1998 yields an unambiguous period estimate of about 11 minutes, which is not incorrect.

In the section "Reprocessing of the 1998 radar data" the echo power spectra bandwidth from June 6, 1998 were included in the post-processing. Figure 7 shows that these spectra have a much lower SNR than the spectra from June 7 and 8, however Table 3 gives an estimate of the Doppler broadening of these spectra with an error of 2 Hz, as for the spectra of

June 7 and 8, which raises doubts about the accuracy of the bandwidth estimate. Including these data in the model with the same weights may introduce inaccuracies into the final results of the asteroid size estimate.

In the section "Astrometry and non-gravitational forces" the authors improve the orbital parameters of asteroid 1998 KY26 considering the non-gravitational accelerations. For this purpose, the astrometric positions obtained by the authors in 2024 and the observations of the VLT and Subaru telescopes obtained during the 2020 close approach are taken. As a result, the parameter A2 was determined, which agrees well with the value obtained by Davide Farnocchia ([https://ssd.jpl.nasa.gov/tools/sbdb_lookup.html#/?sstr=1998 KY26&view=OPC](https://ssd.jpl.nasa.gov/tools/sbdb_lookup.html#/?sstr=1998%20KY26&view=OPC)), however, the authors do not provide such important values as the RMS of the obtained solution, the number of observations used, the physical model and numerical ephemerides, and finally the orbital elements themselves with errors. I consider it necessary to supplement the section with this data, to enable comparison with other solutions. Questions are also raised by the fact that the solution did not use the 1998 observations, which in addition to optical astrometry include 2 radar measurements of delay and 2 measurements of the Doppler shift of the echo signal frequency. For example, in the solution of Davide Farnocchia ([https://ssd.jpl.nasa.gov/tools/sbdb_lookup.html#/?sstr=1998 KY26&view=OPC](https://ssd.jpl.nasa.gov/tools/sbdb_lookup.html#/?sstr=1998%20KY26&view=OPC)), it was possible to combine observations from 1998 to 2024 taking into account non-gravitational accelerations.

I would like to separately praise the authors for their long-term mid-IR flux predictions for the James Webb Space Telescope, which is the only one (before the arrival of Hayabusa2#) in 2028 will be able to confirm or refute the results obtained in this paper.

Overall, I consider this work to be a very important and undoubtedly highly commendable scientific study, and with the correction of the above-mentioned comments, I recommend this article for publication in Nature Communications.

Reviewer #2

(Remarks to the Author)

Review comments for the article "Hayabusa2# mission target 1998 KY26 preview: a small optically bright rapid rotator" by Santana-Ros et al.

The wording of the article is clear and shows specific results. The main result is the determination of the size and rotation period of the object 1998 KY26 which is the target of the Hayabusa2 mission.

The results are extremely important for the success of the mission as the spacecraft must know the size and its rotation period for planning and approach.

The key result of this work is to report a size of 11 metres, half that previously reported, and a rotation period of 5.3 minutes, twice as fast as previous reports.

The observations from this campaign, which were combined with data obtained in 1998, were crucial for the determination of the rotation period of the object and for determining the shape of the object, using the inversion of the light curve obtained at large phase angles.

The article explains in a consistent way the observations made, the results obtained and the implications of these results. The article highlights the need to combine light curve data with radar data for the correct determination of the size and rotation period.

Our suggestions for a better interpretation of the article and identifying parts that are not clear are:

- In the abstract it is made clear that a monolithic object is most likely, but the possibility of a rubble type object is not ruled out. This is discussed in the Discussion section, line 172, although it is not clear whether a rubble pile is possible because of the cohesion calculations. We would like to clarify this discussion to be consistent with the abstract.

- We understand that the spectral identification as an E-type is only due to the high albedo. This was obtained using the phase curves. We recommend if possible to expand on this aspect which is not clear to the reader. In figure 5 we see the spectral groups and the 1998 KY26 data with a large error. It would be convenient to add a graph showing the five griz magnitudes at the VLT, so that the shape of the spectrum can be appreciated.

- It is not clear the discussion in the paragraph of the Discussion section, line 172 about the cohesive strengths of 200 - 300 Pa and the maximum limit in figure 4 of 20 PA. In particular the sentence 'This low cohesive strength level makes it possible for a rubble pile structure to exist at this body size and fast rotation'. We recommend more clarity between this paragraph (line 172) and the caption of figure 4.

- It would be nice if it were made clear in figure 2 that the Z-axis is the axis of rotation of the body. As it is commented at some point in the main text.

- The Methods section is clear and we have no comments.

Minor details

- Figure 1 and figure 3, enlarge the font size which is difficult to see.

- line 179 mentions the escape velocity 'given their sub-cm escape velocities' ... it is a velocity, so the time is missing..., sub-cm per second, per hour?

- Line 71... there is a typo. 1998 KY26 26

Reviewer #3

(Remarks to the Author)

I co-reviewed this manuscript with one of the reviewers who provided the listed reports. This is part of the Nature Communications initiative to facilitate training in peer review and to provide appropriate recognition for Early Career Researchers who co-review manuscripts.

Reviewer #4

(Remarks to the Author)

This paper studies the physical characteristics of asteroid 1998 KY26, which provides an up-to-date comprehensive understanding of the target of Hayabusa2#. Through photometric observations, lightcurve inversion and analysis of radar data, the authors have determined key parameters such as the asteroid's rotation period, albedo, shape model, size and plausible hypotheses of the internal structure. The results offer scientific insights and inputs for the design of the upcoming Hayabusa2# mission. The paper is generally well written and in good order. The results presented are certainly interesting. My primary concerns are detailed below. I will recommend the acceptance for publication only if these points are properly addressed.

General comments:

The paper presents key optical observation data and the corresponding analysis from 1998 KY26's close flyby of Earth in 2024, providing high-confidence measurements of its rotation period, spin orientation, size, and basic shape, which are of significant reference value for the design of engineering missions. However, the paper does not provide sufficient discussion on the scientific implications of these key physical properties, such as the possible origins of its retrograde and rapid spin state. The rapid rotation could result from impacts between space objects, tidal disruption during close encounters with major planets, or the YORP effect (which is particularly significant for small objects like KY26), etc. Also, we expect further explanations on the conflicts between the outgassing theory and absence of dust particles from the observational data (Line 129-134).

Line 72 "The derived strength level of 1998 KY26 is much smaller than the reported cohesive strengths of a few-hundred-metre diameter rubble pile objects" is misleading. The theoretical and numerical simulations by FEM in this study only gives the minimum strength required to maintain the structural integrity, which can not be taken as an assessment of the strength level. The actual strength level might be comparable to that of hundred-metre-sized objects. Besides, The strength threshold calculated using finite element models is not the same as that calculated using discrete element models. This paper does not provide verification of structural integrity using a discrete element numerical model, and therefore the conclusion that "a fine-grained rubble-pile structure is theoretically possible" lacks the necessary support (although I personally agree with this conclusion).

This work highlights the value of combining multiple techniques to study decametre-scale objects, including photometric observations, taxonomy, shape modeling and analysis of the internal structure. However, as This study highlights the value of combining multiple techniques to investigate decametre-scale small bodies, including photometric observations, taxonomy, shape modeling, and internal structure analysis. However, the paper lacks a thorough explanation of the technical approach for integrating these methods. These characterization techniques are not isolated from each other, but rather work together to provide the minimum constraints on the target's properties. It is recommended to include further discussion on the specific methods used and the general applicability of these approaches.

Specific Comments

1. Line 40: The spelling and font of the word "rendez-vous" are incorrect.
2. Line 192: The phrase "... decimetre-sized asteroids" should be corrected to "... decametre-sized asteroids".
3. Line 90: The phrase "yields to a smaller ..." should be corrected to "yields a smaller ...".

Version 1:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

Thanks to the authors, for thoroughly answering all my questions, correcting inaccuracies, and supplementing the publication with missing explanations, which allows me to recommend this article for publication in Nature Communications.

Reviewer #2

(Remarks to the Author)

After reading the new version of the article and also the responses to the different reviewers, we believe that the article is ready for publication.

We have noted that all the responses to all the reviewers have been fixed.

Reviewer #3

(Remarks to the Author)

I co-reviewed this manuscript with one of the reviewers who provided the listed reports. This is part of the Nature Communications initiative to facilitate training in peer review and to provide appropriate recognition for Early Career Researchers who co-review manuscripts.

Reviewer #4

(Remarks to the Author)

The revised version of the article has addressed most of my concerns. However, I need to point out that regarding the second issue, the conclusion about the consistency between DEM and FEM methods is conditional.

The FEM method studies the macroscopic mechanical properties of granular materials through coarse-graining, but the feasibility of this coarse-graining approach depends on whether the granular aggregates exhibit uniform mechanical properties. For a decameter-scale rubble-pile asteroid, considering the particle sizes observed in previous missions, whether its granular system can be properly averaged remains a question that requires further discussion.

This comment raises an important methodological consideration about the applicability of continuum-based FEM modeling to small rubble-pile asteroids. The reviewer acknowledges that FEM and DEM can produce consistent results under certain conditions, but appropriately questions whether those conditions (particularly regarding homogeneity of the granular medium) necessarily hold true for 10-meter-scale objects like 1998 KY26, given what we know about actual asteroid surface properties from missions like Hayabusa2 and OSIRIS-REx. This suggests the structural analysis conclusions might benefit from additional caveats or discussion of these scale-dependent modeling limitations.

Version 2:

Reviewer comments:

Reviewer #4

(Remarks to the Author)

The author clarified the applicable scenarios for the consistency conclusions between FEM and DEM. I have no further revision suggestions.

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REVIEWER COMMENTS

Reviewer #1:

The authors explain the obtained result by large (>60 deg) phase angles, at which more complex patterns on the light curves arise, caused by shading effects for non-convex shapes and angular characteristics for convex shapes. At the same time, the possibility is not considered, for example, that small decameter bodies have a more complex rotation than only around its principal axis (the so-called Tumblers), which could explain the change in the period at large phase angles.

We did not detect any additional periodicities in our lightcurve data that would be indicative of a non-principal axis (tumbling) rotation state. Furthermore, both lightcurve inversion methods employed in our analysis inherently assume rotation about a principal axis; such methods are unable to converge if this condition is not met. Based on this, we conclude that a tumbling state is incompatible with the observed lightcurves. Instead, the newly derived spin period of 5.35 minutes—almost exactly half the period reported by Ostro et al.—provides a consistent explanation for the full set of lightcurves across all observing geometries, including those from 1998. Ostro et al. selected the 10.7-minute period as the most plausible solution for the 1998 dataset, as it yielded a lightcurve with two minima. However, we demonstrate that this longer period fails to reproduce the lightcurves obtained at other geometries. In contrast, the 5.35-minute spin solution fits the full dataset, producing a single-minimum lightcurve at the 1998 geometry, attributable to the object's shape as viewed under specific aspect and low phase angle conditions.

We have updated Figure 1 with a comparison of the fits of the two spin solutions to the lightcurves, showing that the 5.35 min solution provides a better fit. We have also included the following sentence in the Results section, in order to clarify that the object is not a tumbler:

“Neither our Fourier analysis of the lightcurves nor the application of lightcurve inversion techniques revealed any evidence for a secondary periodicity indicative of a tumbling state. This strongly suggests that the object rotates about its principal axis.”

Figure 1 clearly shows the poor representation of the June 2, 1998 observations by the red curve and the large errors in the photometric observations on June 12, 2024, potentially taking different approximations. I believe that it is necessary to supplement the graphs in Figure 1 with curves for an 11-minute period, and to provide in the text the values of the standard deviations of the presentation of photometric observations for periods of 5 and 11 minutes for each graph. It is also necessary to explain in more detail why at large phase angles we do not obtain a false value for the period, since subsequent results of the study (size, shape, etc.) obtained based on this new estimate of the period of 5 minutes.

We have updated Figure 1 with a comparison between the fit to the lightcurves with our new non-convex model and a spin period of 5.35 min versus the fit provided by the shape model presented in Ostro et al. 1999 with a period of 10.70 min. While both models provide a good

fit for the lightcurves obtained at lower phase angles, only the new non-convex model can explain the observations at larger phase angles. Please, notice that for fit of the model from Ostro et al. 1999, we had to recompute the rotational phase in order to fit each lightcurve. Overall, the new non-convex model with a 5.35 min spin fits the data with an $\text{RMS} = 0.106$, while the fit of the model from Ostro et al. with a 10.70 min results in an $\text{RMS} = 0.192$.

In addition to a new Figure 1, we have added the following description to the manuscript:

“In Fig. 1, we compare the lightcurve fits of the non-convex model presented in this paper (using a 5.35 min spin period) with the shape model from Ostro et al. (1999) (using a 10.70 min spin period). The non-convex model fit yields an RMS of 0.106, while the Ostro et al. model results in an RMS of 0.192. Both models provide a good fit to the lightcurves observed at lower phase angles (as seen in the geometry of Ostro et al.), but only the non-convex model with a 5.35 min spin period accurately fits the lightcurves obtained at larger phase angles.”

I propose to move the clarification in lines 443-445 (regarding the poor photometry on October 27, November 1 and 7) to the beginning of the Results section, since this information is necessary to present the overall picture of the data used.

Text moved as suggested by the reviewer.

In lines 70-71, it is also necessary to add the astrometric observations of 2020, which were used in the study to determine the non-gravitational parameters.

A sentence describing the 2020 astrometric observations has been added to the Results section. We have also clarified in the Methods that we have used the whole available observation arc from 1998 to 2024 in our study of the non-gravitational parameters, added the RMS value of the best orbit solution and included a table with the orbital elements obtained.

“With this model, we attempted to fit the entire observation arc from 1998 to 2024. The weighted RMS of the best obtained solution is 0.437, and the resulting orbital elements are presented in Table.~\ref{tab:orbital_elements}.”

I also propose to change (soften) the statement in lines 73-74 that the period obtained by Steven Ostro et al. in 1999 is "not correct". This is not entirely correct, since the finest-time-resolution photometric light curves of 1998 yields an unambiguous period estimate of about 11 minutes, which is not incorrect.

The sentence has been rephrased to “The photometric observations were obtained under a variety of viewing geometries (...), suggesting that the inferred spin period is half of the value originally published by Ostro et al”.

In the section "Reprocessing of the 1998 radar data" the echo power spectra bandwidth from June 6, 1998 were included in the post-processing. Figure 7 shows that these spectra have a much lower SNR than the spectra from June 7 and 8, however Table 3 gives an estimate of the Doppler broadening of these spectra with an

error of 2 Hz, as for the spectra of June 7 and 8, which raises doubts about the accuracy of the bandwidth estimate. Including these data in the model with the same weights may introduce inaccuracies into the final results of the asteroid size estimate.

Please note the relative ratios of the Doppler broadening error to the bandwidth itself. On June 6, an error of 2 Hz represents 30% of the bandwidth, on June 7, an error of 2 Hz represents 20% of the bandwidth, and on June 8, an error of 2 Hz is equivalent to 15% of bandwidth. Thus, our measurement method takes into account the differences in SNRs from day to day.

In order to clarify this in the paper, we have added the following sentences in section "Reprocessing of the 1998 radar data":

"We did a Monte Carlo type of fit to the bandwidths observed from June 6-8, Table 3, based on Eq. 1. Figure 7 shows rotationally unresolved spectra, based on the data sum obtained during the same observing interval. As such, they represent maximum observed bandwidths and the largest physical extents of the object recorded on each day."

"The modelling only included the cw spectra from June 7 and 8, 1998 because the SNRs were sufficiently strong on these days, and the rotation of the object was resolved. For the analysis we describe in this section, we do not use the rotationally resolved spectra, but long interval sums. This allows us to include the data from June 6, (Figure 7). These data had lower SNRs, but the echo is clearly visible, and we found that it significantly help constrain the pole direction as well as the object's size, as seen by comparing the panels in Figs 8."

Plus this sentence in the caption of Table 3:

"On June 6, an error of 2 Hz represents 30% of the bandwidth, on June 7, an error of 2 Hz represents 20% of the bandwidth, and on June 8, an error of 2 Hz is equivalent to 15% of bandwidth. Thus, our measurement method also takes into account the differences in SNRs from day to day."

In the section "Astrometry and non-gravitational forces" the authors improve the orbital parameters of asteroid 1998 KY26 considering the non-gravitational accelerations. For this purpose, the astrometric positions obtained by the authors in 2024 and the observations of the VLT and Subaru telescopes obtained during the 2020 close approach are taken. As a result, the parameter A2 was determined, which agrees well with the value obtained by Davide Farnocchia ([https://ssd.jpl.nasa.gov/tools/sbdb_lookup.html#/?sstr=1998 KY26&view=OPC](https://ssd.jpl.nasa.gov/tools/sbdb_lookup.html#/?sstr=1998%20KY26&view=OPC)), however, the authors do not provide such important values as the RMS of the obtained solution, the number of observations used, the physical model and numerical ephemerides, and finally the orbital elements themselves with errors. I consider it necessary to supplement the section with this data, to enable comparison with other solutions. Questions are also raised by the fact that the solution did not use the 1998 observations, which in addition to optical astrometry include 2 radar measurements of delay and 2 measurements of the Doppler shift of the echo signal frequency. For example, in the solution of Davide Farnocchia

(https://ssd.jpl.nasa.gov/tools/sbdb_lookup.html#/?sstr=1998 KY26&view=OPC), it was possible to combine observations from 1998 to 2024 taking into account non-gravitational accelerations.

The Methods section includes now the root-mean-square (RMS) residual of the orbital fit, the full set of orbital elements (Table 5), and a note clarifying that the orbit determination was based on the complete observational arc spanning from 1998 to 2024.

“With this model, we attempted to fit the entire observation arc from 1998 to 2024. The weighted RMS of the best-fit solution is 0.437, and the resulting orbital elements are presented in Table. 5”

I would like to separately praise the authors for their long-term mid-IR flux predictions for the James Webb Space Telescope, which is the only one (before the arrival of Hayabusa2#) in 2028 will be able to confirm or refute the results obtained in this paper.

The predictions for the James Webb Space Telescope are provided in Table 4 and Figure 10. We included in the text now a sentence about the successful JWST-MIRI measurements of the potentially hazardous asteroid 2024 YR4, together with the reference Rivkin et al. (2025). These measurements nicely demonstrate the feasibility of a radiometric study (or size determination) for 1998 KY26 with JWST.

Reviewer #2:

- In the abstract it is made clear that a monolithic object is most likely, but the possibility of a rubble type object is not ruled out. This is discussed in the Discussion section, line 172, although it is not clear whether a rubble pile is possible because of the cohesion calculations. We would like to clarify this discussion to be consistent with the abstract.

The statement is solely coming from the derived cohesive strength values, thus what we can say here is the possibility that KY26 is a rubble pile, without excluding the possibility that it is monolithic. The abstract statement was updated as follows:

“The derived cohesive strength levels necessary to keep the structure intact, which is less than 20 Pa, suggest a possibility of the asteroid’s rubble pile structure, though this finding does not rule out its monolithic structure.”

- We understand that the spectral identification as an E-type is only due to the high albedo. This was obtained using the phase curves. We recommend if possible to expand on this aspect which is not clear to the reader.

We explain the phase curve analysis thoroughly in the Methods section, emphasizing that the derived absolute magnitude is bound to be so bright that, for the given size, the plausible geometric albedo range is fully in the unique regime of albedos of Xe-type asteroids. We

have further clarified the point in the paragraph of the main part starting as “On 30 May 2024, we obtained ...”.

- In figure 5 we see the spectral groups and the 1998 KY26 data with a large error. It would be convenient to add a graph showing the five griz magnitudes at the VLT, so that the shape of the spectrum can be appreciated

We have included a new figure (Figure 6) with the griz magnitudes measured at the VLT, compared with the B, C, X, S and V spectral templates. We have also included the following sentence, clarifying that our measurements are not compatible with S and V classes:

“In Fig. 6, we compare our griz measurements with the spectral templates of the major asteroid taxonomic classes, showing that our data are compatible within 2σ with the B, C, and X taxonomic classes, but deviate from the S and V class due to discrepancies at $0.47\ \mu\text{m}$ ”

- It is not clear the discussion in the paragraph of the Discussion section, line 172 about the cohesive strengths of 200 - 300 Pa and the maximum limit in figure 4 of 20 PA. In particular the sentence ‘This low cohesive strength level makes it possible for a rubble pile structure to exist at this body size and fast rotation’. We recommend more clarity between this paragraph (line 172) and the caption of figure 4.

We have clarified the discussion of KY26's cohesive strength in the manuscript.

Our structural analysis shows that KY26 requires a cohesive strength in the range of 4–20 Pa to avoid mechanical failure due to its rapid rotation. We refer to this as the *minimum cohesive strength*, as presented in the second-to-last paragraph of the Results section. This threshold represents the lower bound necessary for KY26 to remain structurally intact. Therefore, if KY26 had a cohesive strength below this range, it would not be able to maintain its current shape and should have undergone disruption—an outcome inconsistent with its observed stability.

We note that the cohesive strengths of other small bodies have typically been constrained through observations of their failure events. As cited in the previous manuscript version, for example, a Type-1 surface crack on comet 67P/Churyumov-Gerasimenko suggests an upper cohesive strength of ~300 Pa [Hirabayashi et al., 2016], while the rotational breakup of P/2013 R3 also indicates an upper limit near ~300 Pa [Hirabayashi et al., 2014]. Both bodies are believed to be rubble piles.

Given that KY26's required minimum cohesive strength is significantly lower than the inferred upper cohesive strengths of known rubble-pile bodies, we conclude that KY26 could indeed be a rubble pile while still maintaining structural integrity under its current spin rate.

To make this interpretation clearer, we have revised the first sentence of the paragraph discussing structural analysis as follows:

“The derived minimum cohesive strength level of 1998 KY26 ranges between 4 and 20 Pa (Figure 4), much smaller than the reported cohesive strengths of a few-hundred-metre diameter rubble pile objects, about 200 – 300 Pa.”

References

Hirabayashi, M. et al. Fission and reconfiguration of bilobate comets as revealed by 67P/Churyumov–Gerasimenko. *Nature* 534, 352–355, 10.1038/nature17670 (2016).
Hirabayashi, M., Scheeres, D. J., Sánchez, D. P. & Gabriel, T. Constraints on the physical properties of main belt comet P/2013 R3 from its breakup event. *The Astrophys. J. Lett.* 789, L12, 10.1088/2041-8205/789/1/L12580 (2014).

- It would be nice if it were made clear in figure 2 that the Z-axis is the axis of rotation of the body. As it is commented at some point in the main text.

We have added the sentence “The rotation axis is aligned with the Z axis.”.

- Figure 1 and figure 3 , enlarge the font size which is difficult to see.

We have updated Figures 1 and 3 with a larger font size.

- line 179 mentions the escape velocity ‘given their sub-cm escape velocities’ ... it is a velocity, so the time is missing..., sub-cm per second, per hour?

Corrected.

- Line 71... there is a typo. 1998 KY26 26

Corrected.

Reviewer #4:

The paper presents key optical observation data and the corresponding analysis from 1998 KY26’s close flyby of Earth in 2024, providing high-confidence measurements of its rotation period, spin orientation, size, and basic shape, which are of significant reference value for the design of engineering missions. However, the paper does not provide sufficient discussion on the scientific implications of these key physical properties, such as the possible origins of its retrograde and rapid spin state. The rapid rotation could result from impacts between space objects, tidal disruption during close encounters with major planets, or the YORP effect (which is particularly significant for small objects like KY26), etc. Also, we expect further explanations on the conflicts between the outgassing theory and absence of dust particles from the observational data (Line 129-134).

We appreciate the reviewer’s insightful comment. We would like to clarify that the primary goal and scope of this manuscript are to demonstrate the relevance of our findings to Planetary Defense, particularly in the context of the Hayabusa2# mission. Our key contribution lies in presenting the first demonstration of how coordinated observational

techniques and modeling approaches can effectively constrain the physical properties of a small asteroid, approximately 10 meters in diameter.

As described in the manuscript, KY26's small size limits conventional observational interpretations. Nonetheless, we were able to derive reliable estimates of its spin state, size, taxonomy, orbital perturbation, and structural properties—parameters that are essential for assessing asteroid deflection strategies and, therefore, have direct implications for Planetary Defense.

While we are confident in the quality of our observational data, we acknowledge the limited volume of data currently available, which restricts broader scientific application. In this context, we deliberately avoided further discussion in order to maintain a rigorous and focused narrative aligned with our stated objectives.

Regarding the tension between the outgassing hypothesis and the lack of observed dust particles, this may be attributable to KY26's small size and relatively high albedo. A more comprehensive understanding of the role of solar radiation pressure in such an environment would benefit from further dedicated studies.

We find the reviewer's suggestions for a deeper scientific discussion both valuable and thought-provoking, and we believe they point toward promising directions for future research. However, such discussions extend beyond the scope of the present study, which is intentionally focused on supporting Planetary Defense and mission operations through well-constrained, observation-based insights.

Line 72 “The derived strength level of 1998 KY26 is much smaller than the reported cohesive strengths of a few-hundred-metre diameter rubble pile objects” is misleading. The theoretical and numerical simulations by FEM in this study only gives the minimum strength required to maintain the structural integrity, which can not be taken as an assessment of the strength level. The actual strength level might be comparable to that of hundred-metre-sized objects. Besides, The strength threshold calculated using finite element models is not the same as that calculated using discrete element models. This paper does not provide verification of structural integrity using a discrete element numerical model, and therefore the conclusion that “a fine-grained rubble-pile structure is theoretically possible” lacks the necessary support (although I personally agree with this conclusion).

Response to the comment: “The theoretical and numerical simulations by FEM in this study only give the minimum strength required to maintain the structural integrity, which cannot be taken as an assessment of the strength level.”

We thank the reviewer for the thoughtful feedback. We would like to respectfully refer the reviewer to our response to Reviewer 2, as both comments raise similar points. In the manuscript, we clarify that our finite element method (FEM) analysis is specifically intended to determine the *minimum cohesive strength* required to prevent structural failure under KY26's rapid rotation. This analysis does not aim to measure the actual cohesive strength of the body, but rather to establish a lower bound necessary for its physical stability. We believe this distinction is now more clearly articulated in the revised manuscript.

Response to the comment: “The strength threshold calculated using finite element models is not the same as those calculated using discrete element models.”

We acknowledge and value the reviewer’s observations. However, we respectfully disagree with the implication that finite element models (FEM) are fundamentally inconsistent with discrete element models (DEM) in determining strength thresholds. FEM has been extensively validated within the small-body mechanics community and has served as a benchmark against which other methods—including DEM—are often compared. Numerous studies have demonstrated consistency among FEM, DEM, and theoretical models under relevant conditions.

To support this, we refer the reviewer to key comparative studies: Hirabayashi et al. (2015), Hirabayashi (2015), Hirabayashi et al. (2020), and Hirabayashi et al. (2022). These works outline detailed modeling processes and directly compare FEM and DEM results, showing agreement in cohesive strength estimates under similar assumptions.

While it is true that FEM and DEM differ in their treatment of material interactions (continuum vs. granular frameworks), the consistency demonstrated across multiple studies supports the use of FEM as a valid tool for assessing structural thresholds in small bodies like KY26. To clarify this point, we have added a sentence referencing these studies in the first paragraph of the *Internal Structure* section.

“FEM has been validated for the last decade with detailed comparisons with theoretical modeling and discrete element modeling (DEM), demonstrating its consistency and thus becoming one of the standard approaches in small body structural analysis \cite{Hirabayashi2015A, Hirabayashi2015B, Hirabayashi2020, Hirabayashi2022}.”

References:

- Hirabayashi, M., Sánchez, D. P. & Scheeres, D. J. INTERNAL STRUCTURE OF ASTEROIDS HAVING SURFACE SHEDDING DUE TO ROTATIONAL INSTABILITY. *The Astrophys. J.* 808, 63, 10.1088/0004-637X/638808/1/63 (2015).
- Hirabayashi, M. Failure modes and conditions of a cohesive, spherical body due to YORP spin-up. *Mon. Notices Royal Astron. Soc.* 454, 2249–2257, 10.1093/mnras/stv2017 (2015).
- Hirabayashi, M. et al. Spin-driven evolution of asteroids’ top-shapes at fast and slow spins seen from (101955) Bennu and (162173) Ryugu. *Icarus* 352, 113946, 10.1016/j.icarus.2020.113946 (2020).
- Hirabayashi, M. et al. Double Asteroid Redirection Test (DART): Structural and Dynamic Interactions between Asteroidal Elements of Binary Asteroid (65803) Didymos. *The Planet. Sci. J.* 3, 140, 10.3847/PSJ/ac6eff645 (2022).

This work highlights the value of combining multiple techniques to study decametre-scale objects, including photometric observations, taxonomy, shape modeling and analysis of the internal structure. However, as This study highlights the value of combining multiple techniques to investigate decametre-scale small bodies, including photometric observations, taxonomy, shape modeling, and internal structure analysis. However, the paper lacks a thorough explanation of the technical

approach for integrating these methods. These characterization techniques are not isolated from each other, but rather work together to provide the minimum constraints on the target's properties. It is recommended to include further discussion on the specific methods used and the general applicability of these approaches.

We would like to thank the reviewer for raising this point. We have included the following text in the discussion, to summarize the techniques used, highlighting the connections between them.

“The new lightcurves we obtained enabled us to reject the previously published rotation period of 1KY~and to unambiguously determine its rotation period to be (5.35 ± 0.01) min. The lightcurves were acquired at different observing geometries, which allowed us to apply lightcurve inversion methods to obtain the object's spin-axis orientation and shape. In addition, using the newly derived rotation period and shape model, we re-analysed the 1998 radar data, which led to a revised, significantly smaller diameter estimate for 1KY~of (11 ± 2) m. This updated, smaller size is fully consistent with the non-detection by VISIR reported by Beniyama et al. 2025, providing independent validation of our findings. Finally, photometric measurements acquired over a range of phase angles enabled us to model the object's H,G1,G2 phase function, yielding an updated absolute magnitude and placing constraints on its possible taxonomic classification. By combining the derived H value with the revised diameter from our radar analysis, we infer a high geometric albedo, consistent with an Xe-type asteroid.

However, our results also underscore the inherent limitations of remote observation methods.”

1. Line 40: The spelling and font of the word “rendez-vous” are incorrect.

Corrected.

2. Line 192: The phrase “... decimetre-sized asteroids” should be corrected to “... decametre-sized asteroids”.

Corrected.

3. Line 90: The phrase “yields to a smaller ...” should be corrected to “yields a smaller ...”.

Corrected.

Reviewer #4 (Remarks to the Author):

The revised version of the article has addressed most of my concerns. However, I need to point out that regarding the second issue, the conclusion about the consistency between DEM and FEM methods is conditional.

The FEM method studies the macroscopic mechanical properties of granular materials through coarse-graining, but the feasibility of this coarse-graining approach depends on whether the granular aggregates exhibit uniform mechanical properties. For a decameter-scale rubble-pile asteroid, considering the particle sizes observed in previous missions, whether its granular system can be properly averaged remains a question that requires further discussion.

This comment raises an important methodological consideration about the applicability of continuum-based FEM modeling to small rubble-pile asteroids. The reviewer acknowledges that FEM and DEM can produce consistent results under certain conditions, but appropriately questions whether those conditions (particularly regarding homogeneity of the granular medium) necessarily hold true for 10-meter-scale objects like 1998 KY26, given what we know about actual asteroid surface properties from missions like Hayabusa2 and OSIRIS-REx. This suggests the structural analysis conclusions might benefit from additional caveats or discussion of these scale-dependent modeling limitations.

Response to Reviewer

The issue raised here ultimately asks which model (FEM or DEM) is appropriate for 1998 KY26. Our view is that both can be applied, though detailing this issue is beyond the scope of this paper. We replied to the reviewer's comment part by part, and all responses are listed below. We reflected the above statements in Lines 404-407.

"The applied FEM has been validated for the last decade with detailed comparisons with theoretical modeling and discrete element modeling (DEM), demonstrating its consistency and thus becoming one of the standard approaches in small body structural analysis. Both models are widely used to characterize geologic targets of various sizes. Our focus is to roughly calculate the stress field and thus a lower bound of the mechanical strength of 1998 KY26 without adding free parameters. FEM, similar to DEM, can compute a stress field consistent with theoretical prediction."

> However, I need to point out that regarding the second issue, the conclusion about the consistency between DEM and FEM methods is conditional.

1. We believe DEM and FEM are consistent at least for the present problem, which focuses on the stress field calculation in a uniformly rotating body, regardless of its size. A decade of efforts has led to the development of methods for determining (coarse) stress fields in DEM (Zhang et al., 2018) and for interpreting the FEM-driven stress field in terms of the mechanical strengths of geological materials (Hirabayashi et al., 2016). Both models can provide a consistent stress field in a uniformly rotating small asteroid with the theoretical model (Hirabayashi et al., 2022). However, they both have issues detailing small-scale elements in a large target. DEM uses much larger particles than real ones, while FEM needs to use similar sized continuum elements. Our view is that FEM and DEM can characterize monolithic and rubble pile structures by understanding their pros and cons.

Zhang et al. (2018), "Rotational Failure of Rubble-pile Bodies: Influences of Shear and Cohesive Strengths," *ApJ* 857, 15, doi:10.3847/1538-4357/aab5b2

Hirabayashi et al. (2016), "Fission and reconfiguration of bilobate comets as revealed by 67P/Churyumov-Gerasimenko," *Nature* 534, 352-355, doi:10.1038/nature17670.

Hirabayashi et al. (2022), "Double Asteroid Redirection Test (DART): Structural and Dynamic Interactions between Asteroidal Elements of Binary Asteroid (65803) Didymos," *PSJ* 3, 140, doi:10.3847/PSJ/ac6eff

> The FEM method studies the macroscopic mechanical properties of granular materials through coarse-graining, but the feasibility of this coarse-graining approach depends on whether the granular aggregates exhibit uniform mechanical properties. For a decameter-scale rubble-pile asteroid, considering the particle sizes observed in previous missions, whether its granular system can be properly averaged remains a question that requires further discussion.

2. FEM and DEM are size-independent in terms of their applicability because their goals, at least in the present model that concerns the stress analysis, are to solve the momentum equations in continuous and discrete ways. The FEM

application has been tested for targets with various sizes (Hirabayashi and Scheeres, 2019). A clarity to the provided misconception is that FEM does account for heterogeneity. A simple application to an asteroid may be found by Kim and Hirabayashi (2022). However, we did not use structural heterogeneity because we attempted to make our model simple (see our response #4).

Hirabayashi and Scheeres (2019), "Rotationally induced failure of irregularly shaped asteroids," *Icarus* 317, 354-364, doi:10.1016/j.icarus.2018.08.003.

Kim and Hirabayashi (2022), "A Numerical Approach Using a Finite Element Model to Constrain the Possible Interior Layout of (16) Psyche," *PSJ* 3, 122, doi:10.3847/PSJ/ac6b39.

> This comment raises an important methodological consideration about the applicability of continuum-based FEM modeling to small rubble-pile asteroids. The reviewer acknowledges that FEM and DEM can produce consistent results under certain conditions, but appropriately questions whether those conditions (particularly regarding homogeneity of the granular medium) necessarily hold true for 10-meter-scale objects like 1998 KY26.

3. In our view, asserting that this asteroid is a rubble pile is still inconclusive, thus the monolithic option is still possible, which was stated in the abstract, *"The derived cohesive strength levels necessary to keep the structure intact, which is less than 20 Pa, suggest a possibility of the asteroid's rubble pile structure, though this finding does not rule out its monolithic structure."* For clarity, the 20 Pa cohesive strength is a lower bound (Hirabayashi et al., 2022), so it is not the asteroid's actual cohesive strength. The definition is provided in Line 420. If having granular media or monolithic layers is a major factor to argue which FEM or DEM is proper, 1998 KY26 is a challenging question. We do not answer this question, given a limited understanding of this body.

> The reviewer acknowledges that FEM and DEM can produce consistent results under certain conditions, but appropriately questions whether those conditions (particularly regarding homogeneity of the granular medium) necessarily hold true for 10-meter-scale objects like 1998 KY26, given what we know about actual asteroid surface properties from missions like Hayabusa2 and OSIRIS-REx. This suggests the structural analysis

conclusions might benefit from additional caveats or discussion of these scale-dependent modeling limitations.

4. Unlike Bennu and Ryugu, observed by OSIRIS-REx and Hayabusa2, 1998 KY26 has yet to be detailed by spacecraft missions. The properties of 1998 KY26 may exhibit significant differences when compared to those of Bennu and Ryugu, which are one order of magnitude larger in size. This study's critical contribution includes observational constraints on the physical properties of 1998 KY26 under extremely limited conditions. The structural analysis, including stress field and lower-bound strength computation, plays a key role in providing insight into the asteroid's internal structure, but does not rule out any possibility. The stress computation is identical to solving the equilibrium equation in both FEM and DEM. Thus, it is a straightforward and effective method for representing the mechanical strength distribution, a key parameter identified as crucial for planetary defense within the community, without giving any additional free parameters such as structural heterogeneity. We believe that Hayabusa2's rendezvous observation planning will significantly benefit from our observational constraints and structural analysis interpretations.